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Research Paper
PNW-326

October 1984

Site Index and Height Growth Curves for Unmanaged Even-Aged Stands of Western Hemlock and Sitka Spruce in Southeast Alaska

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Abstract

Farr, Wilbur A. Site index and height growth curves for unmanaged even-aged stands of western hemlock and Sitka spruce in southeast Alaska. Res. Pap. PNW-326. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1984.** 26 p.

Height growth and site index curves and equations are presented for unmanaged even-aged stands of western hemlock and Sitka spruce in southeast Alaska. Data were mostly collected in stands that developed after logging.

Keywords: Even-aged stands, site index, increment (height), stem analysis, western hemlock, *Tsuga heterophylla,* Sitka spruce, *Picea sitchensis,* southeast Alaska, Alaska (southeast).

Research Summary

Site index and height growth curves and equations for unmanaged even-aged stands of western hemlock *(Tsuga heterophylla)* (Raf.) Sarg.) and Sitka spruce *(Picea sitchensis* (Bong.) Carr.) were derived from stem analysis of data from tree stems on 91 plots in southeast Alaska.

Site index curves can provide estimates of site index for unmanaged stands if total height and age at breast height are known. Height growth curves can provide estimates of total height if site index and age at breast height are known.

The curves are based on measurements of total height and age at breast height for hemlock or spruce on 1/5-acre plots in southeast Alaska. Sample trees were selected in even-aged stands from among trees containing no visible evidence of past attack by insect or disease and having a diameter at breast height near the quadratic mean diameter of the eight largest diameter hemlock and spruce on the plot.

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Introduction

The site index and height growth equations and curves presented here were developed from data collected in natural, well-stocked, even-aged stands of western hemlock *(Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce *(Picea sitchensis* (Bong.) Carr.) in southeast Alaska. The index age is 50 years at breast height.

The forests of southeast Alaska are part of the hemlock-spruce forest type that occupies a north-south range along the north Pacific coast, extending from near Coos Bay, Oregon, north and west to the Alaska Peninsula, a distance of about 1,800 miles. Within this type, mean site index of Sitka spruce decreases northward at the rate of about 2.6 feet per degree of latitude (Farr and Harris 1979).

The most extensive stands of western hemlock and Sitka spruce occur in southeast Alaska where the type occupies about 12 million acres, about 6 million acres of which is classified as commercial forest land. In Alaska, the type generally consists of virgin stands of western hemlock and Sitka spruce with small percentages of Alaska-cedar *(Chamaecyparis nootkatensis* (D. Don) Spach) and western redcedar (*Thuja plicata* Donn ex D. Don). About 300,000 acres of commercial forest land have been harvested in southeast Alaska since 1900, and 10,000-17,000 acres are now harvested annually. All logging is by clearcutting.

The oldest clearcuts date back to 1910 and are located near sea level adjacent to saltwater. Only since the 1950's have extensive logging roads been built and cutting units placed inland. Abundant moisture and lack of a pronounced summer drought have greatly limited fires, but some older even-aged stands originated after fire and blowdown, mostly at lower elevation.

Even-aged stands of western hemlock and Sitka spruce vary greatly in species composition. Mixed stands are most common. Exceptions are stands of pure hemlock that have developed from a carpet of advance regeneration, or pure stands of spruce that have become established after glacial recession, landslides, fire, or cultural activities.

Taylor's (1934) proportional site index curves for western hemlock and Sitka spruce, based on height at stand age 100 years, have been used in southeast Alaska for 50 years. They are biased at young ages, a feature common to many earlier sets of proportional curves where mean site was not equal over all age classes. Other sets of site index curves have also been prepared for Sitka spruce by Hegyi and others (1979), Stephens and others (1969), and Meyer (1937), and for western hemlock by Hegyi and others (1979), Wiley (1978), and Barnes (1962).

In the late 1960's, dominant and codominant hemlock and spruce were felled and sectioned in 31 plots of blowdown and fire origin in southeast Alaska. Provisional site index curves were then prepared for each species but never published. About the same time Stephens and others (1969) published findings suggesting that stands of blowdown origin may have site qualities much lower than stands on similar soil types originating from logging or fire. Their work suggested that site rejuvenation and available nutrient status may be much poorer after blowdown than after logging or fire and may thus reduce future productivity.

The site index study remained inactive for several years because of these findings and the desire to develop site index curves applicable to stands originating after logging. In 1977, trees on 60 additional plots, located in areas that had been previously logged, were felled and sectioned. A large enough data base was then available for the development of regional site index and height growth equations.

In the intervening years, there have been significant advances in the development of height growth and site index curves. Many nonlinear equation forms have been applied, and differences between equations to predict height growth and site index have been defined (Curtis and others 1974). Site index curves should be used to predict site productivity where present age and total height are known, whereas height growth curves should be used in the development of yield tables to predict future or past height as a function of site index and age.

Data Collection

Two sets of data were used—31 plots taken in 1967 and 1968 and 60 plots taken in 1977. All plots were located in natural, well-stocked, even-aged stands of western hemlock and Sitka spruce (fig. 1). An attempt was made to sample even-aged stands of hemlock and spruce covering a range of sites throughout southeast Alaska. Because of the limited logging history in the region and a preponderance of old-growth timber, it was not possible to sample stands on all the major islands, or at upper elevations. The sample at lower elevations seems to be fairly representative of sites commonly found in southeast Alaska. Several of the 91 plots were later eliminated because they did not have suitable spruce or hemlock site trees; 57 of the plots had suitable hemlock site trees and 71 had suitable spruce site trees (table 1).

The 1967-68 Sample

All plots but one (77 years old) were taken in stands 110 to 180 years of age. All plots were of blowdown or fire origin. Plots were generally one-third to one-half acre in size. Diameter was measured for all trees on each plot, and trees were classified by crown position. Three hemlock and three spruce of quadratic mean diameter among dominants and codominants were felled and sectioned at stump height, at breast height, at 10 feet, and at succeeding 10-foot intervals up the tree.

The 1977 Sample

In 1977, trees on sixty 1/5-acre plots, all of logging origin, were felled and sectioned. Most of the stands were about 50 years old. The oldest was 110. All diameters were measured, and hemlock and spruce representative of the average of the 40 largest diameter trees per acre were felled and sectioned. Trees representative of a fixed number of trees per acre were chosen to avoid the problem of subjective crown classification and to make the tables and equations easier to apply in the field. Use of the average of the 40 largest diameter trees per acre also agrees with procedures used in many areas of the world. It should be noted that this was a change in sampling from that used in 1967 and 1968 where sample trees were representative of the average of dominants and codominants.

All plots were located at elevations below 500 feet, and most were adjacent to saltwater, as most early day logging took place close to the beach. Most stands were 45 to 60 years old at breast height, whereas stands sampled in 1967 and 1968 were 110 to 180 years old.

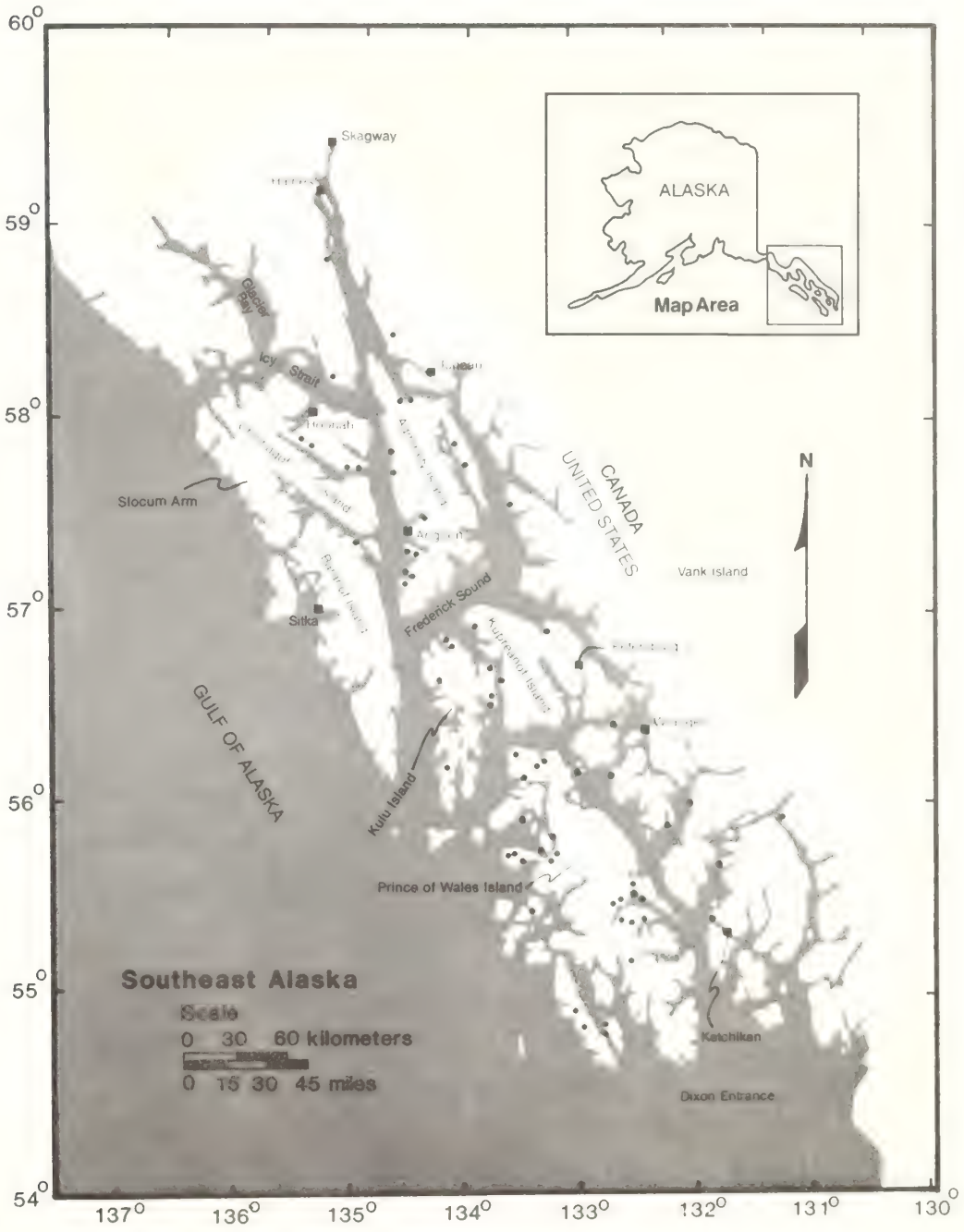

Figure 1.—Locations of site index plots in southeast Alaska.

Table 1—Distribution of plots used to develop the height growth and site index curves for western hemlock and Sitka spruce in southeast Alaska

Range in site index 1/	Western hemlock		Sitka spruce	
	1967-68 sample	1977 sample	1967-68 sample	1977 sample
	Number			
41 - 50	1		1	
51 - 60	2		1	
61 - 70	5	4	5	2
71 - 80	1	8	6	7
81 - 90	6	9	1	7
91 - 100	2	13	9	10
101 - 110		6		16
111 - 120				6
	17	40	23	48
Total plots 2/	57		71	

1/ Index age is 50 years at breast height.
2/ Trees on 91 (1/5-acre) plots were felled and sectioned; 71 of the plots contained suitable hemlock site trees and 57, suitable spruce site trees.

Analysis

Many nonlinear regression equations have been used to fit stem analysis data to the equation of general form,

Height = f(site index, age);

where: f = function.

Some commonly used equations are:

$$HT = (b_1 + b_2S)\ (1\text{-}e^{-b_3SA})^{b_4},$$

$$HT = (b_1 + b_2S)\ (1\text{-}e^{-[b_3+b_4S]A})^{b_5}, \text{ and}$$

$$HT = b_1S^{b_2}(1\text{-}e^{-b_3A})^{b_4Sb_5};$$

where:

HT = total height,
S = site index,
A = age,
e = base of natural logarithms, and
b = least square estimates of the parameters of the equation.

In application, relationships for HT = f(S, A) are generally reversed and used to estimate site index from observed values of height and age because the above equations cannot be used directly to develop site index equations, which are automatically conditioned so that the term $(1\text{-}e^{-bA})\rightarrow 0$ as $A\rightarrow 0$. In the relationship, S = f(HT, A), site index should not go to zero as age goes to zero.

Curtis and others (1974) and Dahms (1975) presented alternative methods for constructing consistent height growth and site index curves in which they independently fit the relationship, S = f(HT, A).

General procedures used to develop the equations and curves for western hemlock and Sitka spruce were suggested by Curtis and others (1974) and Dahms (1975) and were used by Barrett (1978) and Cochran (1979a, 1979b). Included are height and site curves, both developed around a mean height over age curve, as both height and site equations should predict the same values for the mean curve.

In construction of the site index and height growth curves, the general relationships,

$$S - 4.5 \text{ feet} = a + b\ (HT - 4.5 \text{ feet}), \text{ and}$$

$$HT - 4.5 \text{ feet} = c + d\ (S - 4.5 \text{ feet}),$$

were used; and coefficients a, b, c, and d were determined for each 10-year class. Values for b and d were then smoothed over age by stepwise regression. Each equation was forced through 1 at age 50.

Steps used to construct these equations are given in the appendix.

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Results

Estimating Site Index

Separate site index curves were developed for western hemlock (fig. 2) and Sitka spruce (fig. 3) because tests showed that data for the two species could not be pooled. Comparison of figures 2 and 3 shows that the curves are similar at all ages for the higher site classes but are somewhat different at ages greater than 60 for lower site classes.

For more precise estimates of site index, the values in table 2 (hemlock) or table 3 (spruce) can be used to evaluate the equation,

Site index $-$ 4.5 feet $= a_i + b_i$ (height $-$ 4.5 feet);

where:

$i = 1$ for western hemlock and 2 for Sitka spruce.

Equations are also given in the appendix for calculator or computer applications.

Estimation of site index by use of these curves, tables, or equations should be limited to well-stocked, even-aged stands of western hemlock and Sitka spruce.

To apply the site index curves, tables, or equations, use the following procedures:

1. Establish 1/5-acre plots in even-aged, natural stands that are free of residuals from a previous stand and contain no visible evidence of attack by insect or disease.

2. Measure diameter of the eight largest diameter trees (hemlock and spruce only) on each plot, being sure not to include remnants of an earlier stand.

3. Compute quadratic mean diameter of the eight largest diameter trees (hemlock and spruce) per plot (40/acre) and select three hemlock and/or spruce with diameters about that size.

4. Extract an increment core from each tree at breast height to determine age of the tree at breast height.

5. Using the age and total height for each tree, determine site index. Then calculate mean site index for each species.

On the average, dominant hemlock are about 5 years older at breast height than are dominant spruce because small hemlock regeneration is usually present in the understory of old-growth stands. When the old growth is removed, the hemlock has a head start over spruce regeneration that seeds in later. This does not affect estimates of site index as long as site index is estimated from individual tree age and total height.

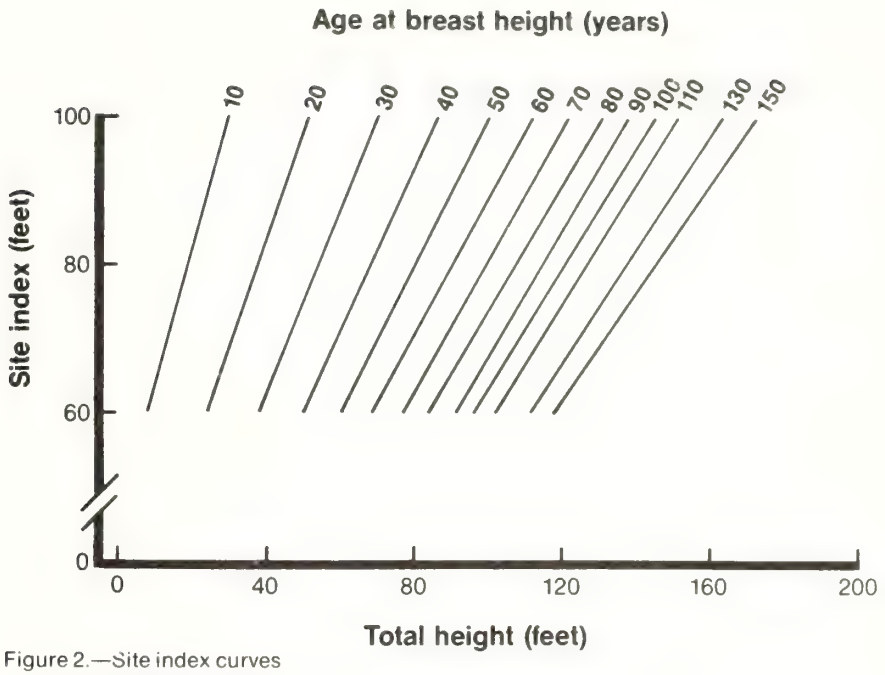

Figure 2.—Site index curves for unmanaged, even-aged western hemlock in southeast Alaska.

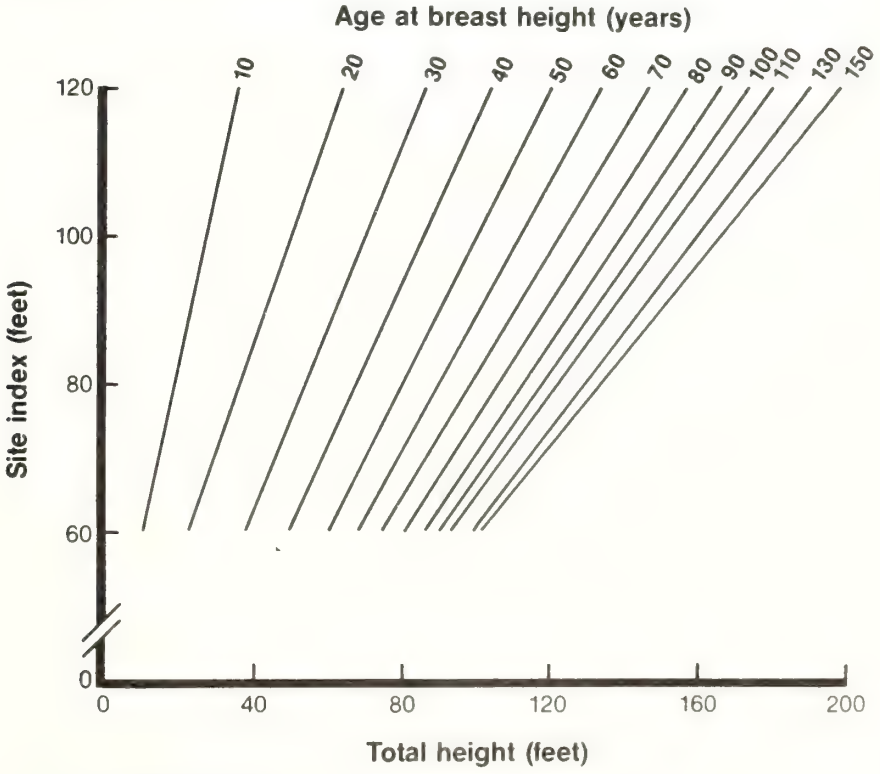

Figure 3.—Site index curves for unmanaged, even-aged Sitka spruce in southeast Alaska.

Table 2—Values for a_1 and b_1 for the family of regressions for estimating site index for western hemlock in southeast Alaska[1/]

Age at breast height	Years between decades: 0		1		2		3		4		5		6		7		8		9	
	a_1	b_1	a_1	b_1	a_1	b_1	a_1	b_1	a_1	b_1	a_1	b_1	a_1	b_1	a_1	b_1	a_1	b_1	a_1	b_1
Years																				
10	49.501	1.787	46.488	1.761	43.679	1.732	41.059	1.701	38.616	1.669	36.334	1.636	34.202	1.604	32.206	1.572	30.336	1.540	28.579	1.510
20	26.926	1.480	25.369	1.452	23.899	1.424	22.507	1.398	21.189	1.373	19.936	1.349	18.745	1.326	17.608	1.304	16.523	1.283	15.485	1.263
30	14.489	1.244	13.533	1.226	12.614	1.208	11.728	1.192	10.873	1.176	10.046	1.161	9.247	1.146	8.471	1.133	7.718	1.119	6.987	1.107
40	6.275	1.095	5.582	1.083	4.906	1.072	4.245	1.062	3.600	1.052	2.969	1.042	2.352	1.033	1.747	1.027	1.153	1.016	.571	1.008
50	0	1.000	.561	.993	-1.113	.986	-1.655	.979	-2.189	.972	-2.714	.966	-3.231	.960	-3.740	.954	-4.242	.949	-4.736	.943
60	-5.223	.938	-5.704	.933	-6.177	.928	-6.644	.924	-7.105	.919	-7.559	.915	-8.008	.911	-8.450	.907	-8.886	.903	-9.317	.900
70	-9.742	.896	-10.161	.893	-10.574	.889	-10.982	.886	-11.384	.883	-11.781	.880	-12.173	.877	-12.559	.874	-12.940	.871	-13.315	.868
80	-13.685	.866	-14.050	.863	-14.409	.861	-14.764	.858	-15.113	.856	-15.457	.853	-15.796	.851	-16.129	.849	-16.458	.846	-16.781	.844
90	-17.099	.842	-17.412	.840	-17.720	.838	-18.023	.836	-18.321	.833	-18.614	.831	-18.902	.829	-19.185	.827	-19.463	.825	-19.736	.823
100	-20.004	.821	-20.268	.819	-20.526	.817	-20.780	.815	-21.029	.814	-21.273	.812	-21.512	.810	-21.747	.808	-21.977	.806	-22.203	.804
110	-22.424	.802	-22.641	.800	-22.853	.798	-23.062	.797	-23.265	.795	-23.465	.793	-23.661	.791	-23.852	.789	-24.040	.787	-24.224	.785
120	-24.404	.784	-24.580	.782	-24.753	.780	-24.922	.778	-25.088	.776	-25.250	.775	-25.410	.773	-25.566	.771	-25.720	.769	-25.871	.768
130	-26.019	.766	-26.164	.764	-26.308	.763	-26.449	.761	-26.588	.760	-26.725	.758	-26.861	.757	-26.995	.755	-27.127	.754	-27.259	.752
140	-27.389	.751	-27.519	.750	-27.648	.749	-27.777	.747	-27.906	.746	-28.035	.745	-28.164	.744	-28.293	.743	-28.424	.742	-28.556	.741
150	-28.689	.741																		

1/ To estimate site index, determine the quadratic mean diameter of the 8 largest diameter trees per 1/5-acre plot; then measure the height and determine age at breast height of at least 3 hemlock near this mean diameter. For each tree, select appropriate a_1 and b_1 values and substitute these values in the equation (site index - 4.5 feet) = a_1 + b_1 (height - 4.5 feet). For example, for a tree 74 years old at breast height and 105 feet in total height, solve the equation (site index - 4.5 feet) = -11.384 + 0.883 (105 feet - 4.5 feet) for a site index of 81.9 feet. Determine the site index for each hemlock. The mean site index determined is the site index for western hemlock on the 1/5-acre plot.

Table 3—Values for a_2 and b_2 for the family of regressions for estimating site index for Sitka spruce in southeast Alaska[1/]

Age at breast height	Years between decades: 0		1		2		3		4		5		6		7		8		9	
	a_2	b_2	a_2	b_2	a_2	b_2	a_2	b_2	a_2	b_2	a_2	b_2	a_2	b_2	a_2	b_2	a_2	b_2	a_2	b_2
Years																				
10	43.220	2.330	42.069	2.143	40.753	1.998	39.327	1.884	37.827	1.792	36.279	1.716	34.705	1.652	33.120	1.598	31.536	1.551	29.963	1.510
20	28.408	1.474	26.879	1.441	25.380	1.412	23.914	1.385	22.486	1.360	21.098	1.338	19.751	1.316	18.448	1.296	17.189	1.278	15.975	1.260
30	14.806	1.243	13.682	1.227	12.603	1.211	11.569	1.197	10.580	1.182	9.634	1.169	8.731	1.155	7.870	1.142	7.050	1.130	6.271	1.117
40	5.530	1.105	4.826	1.094	4.160	1.082	3.529	1.071	2.932	1.060	2.368	1.050	1.836	1.039	1.334	1.029	.862	1.019	.418	1.010
50	0	1.000	-.391	.991	-.758	.982	-1.102	.973	-1.423	.964	-1.723	.955	-2.003	.947	-2.264	.939	-2.507	.930	-2.732	.923
60	-2.942	.915	-3.136	.907	-3.316	.900	-3.482	.893	-3.635	.885	-3.777	.878	-3.908	.872	-4.028	.865	-4.138	.858	-4.239	.852
70	-4.332	.846	-4.418	.840	-4.496	.834	-4.567	.828	-4.633	.822	-4.692	.817	-4.747	.811	-4.798	.806	-4.844	.801	-4.886	.796
80	-4.925	.791	-4.961	.786	-4.995	.781	-5.026	.777	-5.056	.772	-5.083	.768	-5.110	.764	-5.135	.760	-5.159	.756	-5.182	.752
90	-5.205	.748	-5.228	.744	-5.250	.741	-5.273	.737	-5.295	.734	-5.318	.730	-5.341	.727	-5.364	.724	-5.388	.721	-5.412	.718
100	-5.437	.715	-5.463	.712	-5.489	.709	-5.515	.707	-5.543	.704	-5.570	.702	-5.598	.699	-5.627	.697	-5.656	.694	-5.685	.692
110	-5.714	.690	-5.743	.688	-5.772	.686	-5.801	.684	-5.830	.682	-5.858	.680	-5.885	.678	-5.912	.676	-5.937	.674	-5.961	.672
120	-5.984	.671	-6.005	.669	-6.024	.667	-6.041	.665	-6.055	.664	-6.067	.662	-6.075	.661	-6.081	.659	-6.082	.657	-6.080	.656
130	-6.073	.654	-6.062	.653	-6.046	.651	-6.024	.650	-5.997	.648	-5.964	.647	-5.925	.645	-5.878	.643	-5.825	.642	-5.764	.640
140	-5.694	.639	-5.617	.637	-5.530	.635	-5.435	.634	-5.329	.632	-5.213	.630	-5.087	.628	-4.950	.626	-4.801	.624	-4.640	.622
150	-4.467	.620																		

1/ To estimate site index, determine the quadratic mean diameter of the 8 largest diameter trees per 1/5-acre plot; then measure the height and determine age at breast height of at least 3 spruce near this mean diameter. For each tree, select appropriate a_2 and b_2 values and substitute these values in the equation (site index - 4.5 feet) = a_2 + b_2 (height - 4.5 feet). For example, for a tree 74 years old at breast height and 105 feet in total height, solve the equation (site index - 4.5 feet) = -4.633 + 0.822 (105 feet - 4.5 feet) for a site index of 82.5 feet. Determine the site index for each spruce. The mean site index determined is the site index for Sitka spruce on the 1/5-acre plot.

Comparison of Site Indexes of Western Hemlock and Sitka Spruce

Thirty-one plots in the 1977 sample contained western hemlock and Sitka spruce site trees. For these plots, the relationship between site index of the two species was:

Hemlock site index = 24.41 + 0.674 (site index of Sitka spruce)—where the standard error was 1.22, and the coefficient of determination (r^2) was 0.78;

spruce site index = −6.62 + 1.152 (site index of western hemlock)—where the standard error was 0.94, and r^2 was 0.78.

Estimating Height Growth

Height growth curves define the average pattern of height growth in stands of known site quality. They are appropriately used for constructing yield tables but do not provide optimum estimates of site index from measured height and age in a stand (Curtis and others 1974).

Figures 4 and 5 can be used to make rough estimates of mean height of hemlock and spruce representative of the 40 trees of largest diameter per acre. For more precise estimates of mean total height of the 40 trees of largest diameter per acre, use values in tables 4 or 5 in the equation:

Total height − 4.5 feet = $c_i + d_i$ (site index − 4.5 feet).

Equations in the appendix will be useful for those wishing to use a computer program.

Figure 4.—Height growth curves for unmanaged, even-aged western hemlock in southeast Alaska. Heights represent the mean among the 40 largest diameter trees per acre.

Figure 5.—Height growth curves for unmanaged, even-aged Sitka spruce in southeast Alaska. Heights represent the mean among the 40 largest diameter trees per acre.

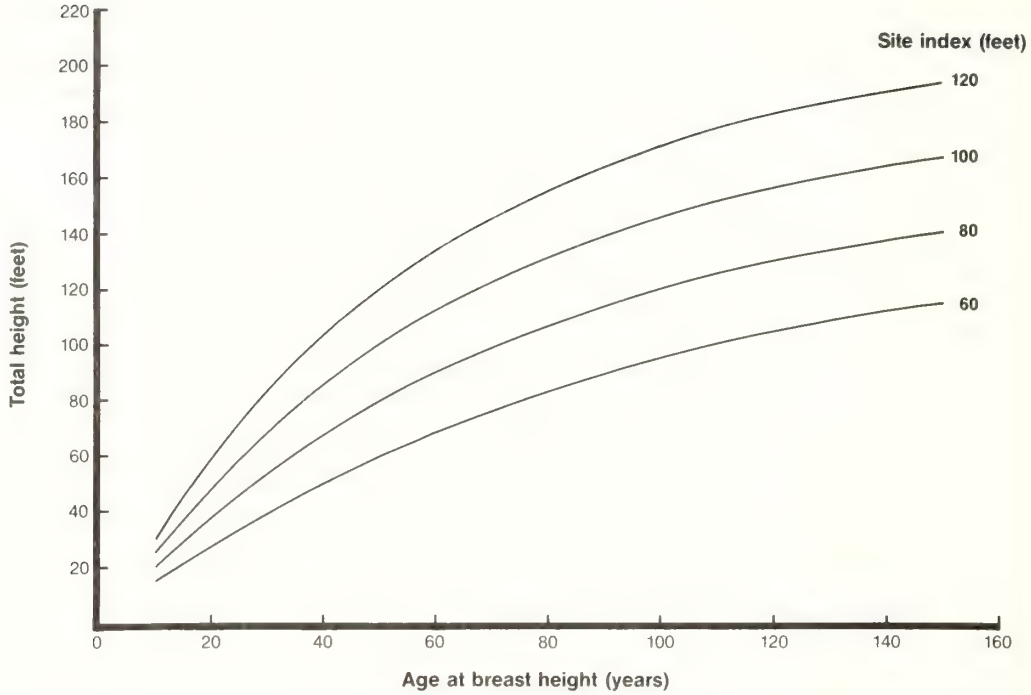

Table 4—Values for c_1 and d_1 for the family of regressions for estimating height of the 40 largest diameter western hemlock trees per acre where site index and age at breast height are known, southeast Alaska[1/]

Age at breast height	Years between decades: 0		1		2		3		4		5		6		7		8		9	
	c_1	d_1	c_1	d_1	c_1	d_1	c_1	d_1	c_1	d_1	c_1	d_1	c_1	d_1	c_1	d_1	c_1	d_1	c_1	d_1
Years																				
10	-0.983	0.239	-0.888	0.261	-0.865	0.285	-0.907	0.309	-1.004	0.333	-1.148	0.358	-1.331	0.383	-1.546	0.409	-1.786	0.434	-2.042	0.459
20	-2.310	.485	-2.582	.510	-2.853	.535	-3.119	.559	-3.375	.583	-3.616	.607	-3.838	.630	-4.039	.653	-4.216	.675	-4.366	.697
30	-4.486	.718	-4.576	.738	-4.634	.758	-4.658	.777	-4.648	.795	-4.604	.813	-4.524	.830	-4.410	.846	-4.260	.862	-4.077	.877
40	-3.859	.891	-3.608	.905	-3.324	.918	-3.008	.930	-2.662	.942	-2.285	.953	-1.881	.963	-1.449	.973	.990	.983	-.507	.992
50	0	1.000	.530	1.008	1.080	1.015	1.651	1.022	2.240	1.029	2.846	1.035	3.468	1.041	4.104	1.046	4.755	1.051	5.417	1.055
60	6.091	1.060	6.775	1.064	7.468	1.067	8.169	1.071	8.877	1.074	9.591	1.077	10.310	1.079	11.033	1.082	11.760	1.084	12.490	1.086
70	13.221	1.088	13.953	1.089	14.686	1.091	15.419	1.092	16.151	1.093	16.882	1.095	17.611	1.096	18.338	1.096	19.063	1.097	19.784	1.098
80	20.502	1.099	21.216	1.099	21.927	1.100	22.633	1.100	23.334	1.100	24.031	1.101	24.722	1.101	25.409	1.101	26.090	1.102	26.766	1.102
90	27.436	1.102	28.101	1.102	28.761	1.102	29.414	1.103	30.062	1.103	30.704	1.103	31.341	1.103	31.972	1.103	32.597	1.103	33.216	1.103
100	33.830	1.104	34.439	1.104	35.042	1.104	35.639	1.104	36.232	1.104	36.819	1.105	37.401	1.105	37.978	1.105	38.550	1.105	39.117	1.106
110	39.679	1.106	40.236	1.106	40.789	1.106	41.338	1.107	41.882	1.107	42.421	1.107	42.957	1.108	43.488	1.108	44.014	1.108	44.537	1.109
120	45.056	1.109	45.570	1.109	46.081	1.110	46.587	1.110	47.090	1.110	47.588	1.111	48.083	1.111	48.573	1.111	49.059	1.112	49.541	1.112
130	50.018	1.112	50.492	1.113	50.960	1.113	51.424	1.113	51.883	1.113	52.337	1.114	52.786	1.114	53.229	1.114	53.667	1.114	54.099	1.114
140	54.524	1.114	54.943	1.115	55.355	1.115	55.759	1.115	56.156	1.115	56.545	1.115	56.925	1.115	57.296	1.115	57.658	1.114	58.010	1.114
150	58.351	1.114																		

1/ Height at a future age of the average among the 40 largest diameter trees per acre may be estimated on land of known site index by selecting c_1 and d_1 values for the appropriate age at breast height. Substitute c_1 and d_1 values into the equation (height - 4.5 feet) = c_1 + d_1 (site index - 4.5 feet). For example, to determine height among the 40 largest diameter trees in a stand of age 85 years on land of known site index 100 feet, solve the equation (height - 4.5 feet) = 24.031 + 1.101 (100 feet - 4.5 feet) for a total height of 133.7 feet.

Table 5—Values for c_2 and d_2 for the family of regressions for estimating height of the 40 largest diameter Sitka spruce trees per acre where site index age at breast height are known, southeast Alaska[1/]

Age at breast height	Years between decades																			
	0		1		2		3		4		5		6		7		8		9	
	c_2	d_2	c_2	d_2	c_2	d_2	c_2	d_2	c_2	d_2	c_2	d_2	c_2	d_2	c_2	d_2	c_2	d_2	c_2	d_2
Years																				
10	-2.590	0.244	-3.020	0.275	-3.413	0.304	-3.767	0.333	-4.081	0.361	-4.357	0.389	-4.595	0.416	-4.796	0.442	-4.962	0.468	-5.095	0.492
20	-5.196	.516	-5.268	.540	-5.312	.562	-5.329	.585	-5.321	.606	-5.290	.627	-5.237	.647	-5.164	.667	-5.071	.686	-4.961	.705
30	-4.833	.723	-4.691	.741	-4.533	.758	-4.362	.774	-4.178	.791	-3.981	.806	-3.774	.822	-3.556	.837	-3.328	.852	-3.090	.866
40	-2.844	.880	-2.590	.893	-2.328	.906	-2.059	.919	-1.782	.932	-1.500	.944	-1.211	.956	-.916	.967	-.616	.978	-.311	.989
50	0	1.000	.315	1.010	.635	1.021	.959	1.030	1.287	1.040	1.620	1.049	1.956	1.059	2.296	1.067	2.640	1.076	2.987	1.085
60	3.337	1.093	3.691	1.101	4.049	1.108	4.409	1.116	4.772	1.123	5.139	1.131	5.508	1.137	5.880	1.144	6.256	1.151	6.634	1.157
70	7.015	1.163	7.398	1.169	7.784	1.175	8.173	1.181	8.565	1.186	8.959	1.191	9.356	1.197	9.755	1.202	10.157	1.206	10.561	1.211
80	10.968	1.215	11.377	1.220	11.788	1.224	12.202	1.228	12.618	1.232	13.036	1.235	13.456	1.239	13.878	1.242	14.302	1.246	14.728	1.249
90	15.155	1.252	15.585	1.255	16.016	1.258	16.448	1.260	16.882	1.263	17.317	1.265	17.754	1.267	18.191	1.269	18.630	1.271	19.069	1.273
100	19.509	1.275	19.949	1.277	20.389	1.279	20.830	1.280	21.271	1.282	21.711	1.283	22.151	1.284	22.590	1.285	23.029	1.286	23.466	1.287
110	23.902	1.288	24.336	1.289	24.769	1.290	25.199	1.291	25.627	1.292	26.052	1.292	26.475	1.293	26.893	1.293	27.309	1.294	27.720	1.294
120	28.127	1.295	28.529	1.295	28.926	1.296	29.318	1.296	29.704	1.296	30.084	1.297	30.457	1.297	30.822	1.297	31.180	1.298	31.531	1.298
130	31.872	1.299	32.205	1.299	32.528	1.300	32.841	1.300	33.143	1.301	33.434	1.301	33.713	1.302	33.980	1.303	34.234	1.304	34.474	1.305
140	34.700	1.306	34.911	1.307	35.106	1.308	35.285	1.309	35.447	1.311	35.591	1.313	35.716	1.314	35.821	1.316	35.907	1.318	35.970	1.321
150	36.012	1.323																		

1/ Height at a future age of the average among the 40 largest diameter trees per acre may be estimated on land of known site index by selecting c_2 and d_2 values for the appropriate age at breast height. Substitute c_2 and d_2 values in the equation (height - 4.5 feet) = c_2 = d_2 (site index - 4.5 feet). For example, to determine the average height among the 40 largest diameter trees per acre in a stand of age 85 years at breast height on land with a known site index of 100 feet, solve the equation (height - 4.5 feet) = 13.036 + 1.235 (100 feet - 4.5 feet) for a total height of 135.5 feet.

Metric Equivalents

1 foot = 0.3048 meter
1 mile = 1.6093 kilometers
1 acre = 0.4047 hectare

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Appendix

Height development of two or three sample trees of each species on each plot was plotted for each tree over individual age at breast height. On the average, hemlock were about 5 years older than spruce, probably because hemlock is very tolerant of shade and is commonly found as advance regeneration in the understory of old-growth stands.

Trees were rejected from further analysis if tops had been damaged or if cross sections showed signs of suppression. Straight-line interpolation was used to estimate mean height for each species at 10-year intervals.

Data for each species and plot were then fit to the equation,

$$\text{Height} - 4.5 \text{ feet} = b_1(1-e^{-b_2 age})^{b_3};$$

where: age = age at breast height.

This flexible nonlinear equation fit the typical sigmoid-shaped height over age curves very well. Coefficients b_1, b_2, and b_3 for each species were then plotted and regressed over site index minus 4.5 feet at age 50 to check for significant outliers. This helped to identify plots with height-growth trends obviously different from regional averages by site class. Several plots were eliminated (Daniel and Wood 1971). Fifty-seven of the plots had suitable hemlock site trees and 71 had suitable spruce site trees.

Data sets for western hemlock and Sitka spruce were then analyzed, generally following procedures outlined by Dahms (1975) and used by Barrett (1978) and Cochran (1979a, 1979b).

The two sets of data (1967-68 and 1977) for each species were analyzed separately because the earlier set came from dominant and codominant trees in 110- to 180-year-old stands of blowdown and fire origin, whereas the 1977 data were from trees representative of the average among the 40 largest diameter trees per acre in 50- to 100-year-old stands of logging origin. Extensive testing using several nonlinear equations, plus Dahms' (1975) procedure, was done to see if the data sets could be pooled. If possible, I wanted to pool some or all of the 1967-68 data with the 1977 data so the height and site index curves could be extended to age 150 years. If the two sets of data for each species could not be pooled, then only the 1977 data set from logged over stands would be used and the height and site curves would be extended only to age 100 years.

The analysis showed no significant difference between the two sets of spruce data, so they were pooled. This meant that, although slightly different components of the overstory were sampled in 1967-68 than in 1977, the curve form describing growth patterns could not be shown to differ.

For hemlock at young ages, there were significant differences between the two sets of data, which suggested some initial suppression in the hemlock from stands of blowdown origin. Beyond age 40 years, there was no significant difference in growth trends for trees representative of the same site. In the final analysis for hemlock, the 1977 data and the 1967-68 data were used for ages greater than 40 years. This eliminated any correlation between the residuals and site and age, or between residuals and height and age, and allowed for the extension of the curves to age 150 years.

This analysis showed that the general shape of the curves is essentially the same whether average dominant and codominant trees are used or the average among the 40 largest diameter trees per acre. What is important is consistency in field application.

Construction of Curves for Western Hemlock

Site index curves.—The basic equation used to construct the site index curves for western hemlock was:

$$S - 4.5 \text{ feet} = a_1 + b_1 (HT - 4.5 \text{ feet});$$

where:

S = site index at age 50 years,
HT = total height, and
a_1, b_1 = least square estimates of the parameters of the equation for western hemlock.

Linear regressions were calculated for each decade from 10 to 150 years. The following estimates were obtained:

Age at breast height	a_1	b_1	r^2	Standard error of the estimate	Observations
(Years)	(Feet)	(Feet)		(Feet)	(Number)
10	49.5115	1.7859	0.43	8.65	40
20	27.0813	1.4827	.72	5.93	40
30	13.9337	1.2503	.88	3.82	40
40	8.1965	1.0605	.96	2.35	40
50	0	1.0000	1.00	0	40
60	-3.2754	.9094	.98	2.08	30
70	-9.4892	.8914	.95	2.94	20
80	-15.8885	.8806	.94	3.18	20
90	-18.4797	.8423	.93	3.78	18
100	-21.9476	.8244	.89	4.69	17
110	-18.9048	.7631	.85	4.88	14
120	-30.9645	.8191	.90	4.29	10
130	-30.5959	.7826	.89	4.64	10
140	-25.1111	.7222	.88	5.18	8
150	-4.2578	.5673	.49	8.58	4

The b_1 values were then smoothed (fig. 6) by fitting a logarithmic equation that described b_1 as a function of age at breast height. The equation was forced through 1 at age 50.

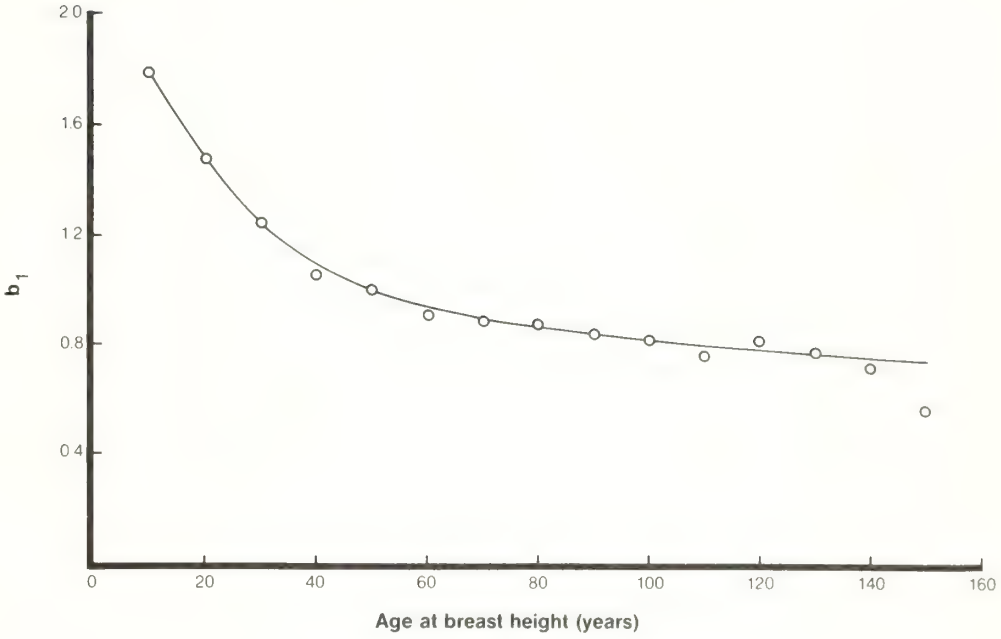


Figure 6.—b_1 values for western hemlock in the equation (S − 4.5 feet) = $a_1 + b_1$ (HT − 4.5 feet) as a function of age. Plotted points are actual b_1 values. Solid line is expressed by the equation $\hat{b}_1 = e^{x_1}$. Coefficient x_1 is defined in the text. Standard error is 0.00071 and r^2 is 0.9922.

Coefficient b_1 turned sharply downward at age 150. Because the logarithmic equation (using natural logs) is very sensitive, the regression curve also turned sharply downward beyond age 140 years. To correct for this, the data were smoothed to remove extreme variation in b_1 over age at ages 140 to 150 years.

The derived equation was:

$$\begin{aligned} x_1 = \log_e(\hat{b}_1) = & -0.5004715 + 1.082291\ (\log_e age) \\ & - 0.2673998\ (\log_e age)^2 \\ & + 8.355966 \times 10^{-6}\ (\log_e age)^8 \\ & - 7.751521 \times 10^{-9}\ (\log_e age)^{12} \\ & + 7.142552 \times 10^{-27}\ (\log_e age)^{36}; \end{aligned}$$

where: age = age at breast height.

Mean height for each 10-year age at breast height was also calculated and plotted (table 6 and fig. 7). Number of plots and mean site index in each decadal age decreased beyond age 50 years, so mean height at each decadal age beyond age 50 did not represent the height corresponding to mean site index at age 50 years (87.70). Heights were therefore adjusted by use of the c_1 and d_1 coefficients for each age class and mean site index at age 50 in the equation,

$$HT = 4.5 + c_1 + d_1\ (87.70 - 4.5).$$

Table 6—Regression coefficients for western hemlock from the equation (height − 4.5) = c_1 + d_1 (site − 4.5) by 10-year age class, and corrections for mean height after age 50, southeast Alaska

Age at breast height	c_1	d_1	r^2	Standard error of estimate	Observations	Mean height	Corrected	
							Mean height 1/	Adjusted mean height 2/
Years				Feet	Number	- - - - - - Feet - - - - - - - -		
10	-0.9758	0.2384	0.43	3.16	40	23.36	23.36	23.36
20	-2.6963	.4873	.72	3.40	40	42.35	42.35	42.35
30	-3.4674	.7075	.88	2.88	40	59.90	59.90	59.90
40	-4.2922	.9016	.96	2.17	40	75.22	75.22	75.22
50	0	1.0000	1.00	0	40	87.70	87.70	87.70
60	5.5180	1.0732	.98	2.26	30	87.90	99.31	99.31
70	14.3348	1.0687	.95	3.22	20	93.00	107.75	107.75
80	22.4161	1.0725	.94	3.51	20	101.35	116.15	116.15
90	27.9638	1.0994	.92	4.32	18	107.83	123.93	123.93
100	35.6033	1.0827	.89	5.37	17	114.65	130.18	130.18
110	39.1424	1.1117	.84	5.89	14	124.00	136.14	136.14
120	46.1402	1.1028	.89	4.98	10	128.50	142.39	142.08
130	49.2752	1.1335	.87	5.58	10	133.80	148.08	147.18
140	47.0255	1.2161	.86	6.73	8	140.00	152.71	151.58
150	80.9291	.8702	.24	10.62	4	157.00	157.83	155.20

1/ After age 50, heights were calculated from the equation height = 4.5 + c_1 + d_1 (87.70 - 4.5) to adjust for decreasing numbers of observations and changing mean site index.

2/ Calculated heights for ages 120 years and older resulted in a poor fit of the combined equation so they were adjusted downward to give the height and site curves a more realistic fit; otherwise, they would turn upward after age 140.

Figure 7.—Mean height of sectioned western hemlock as a function of age at breast height for each 10-year age class. Plotted points are actual mean heights minus 4.5 feet. Solid line is expressed by the equation ($\hat{HT}$ − 4.5 feet) = e^{x_2}, where x_2 is defined in the text. Standard error is 0.374 and r^2 is 0.9993.

Even then, there was a problem at ages greater than 120 years because of few observations. This was corrected by adjusting the mean height over age curve at upper ages (table 6). Adjustments of 1 to 3 feet were made to smooth the curves so as to avoid having curves that turned sharply upward or downward beyond age 120 years. These adjustments were made and tested to avoid any correlation between site index residuals and height and age.

The derived equation was:

$$x_2 = \log_e(\hat{HT} - 4.5 \text{ feet}) = 0.3621734 + 1.149181\ (\log_e \text{age}) - 0.005617852\ (\log_e \text{age})^3 - 7.267547 \times 10^{-6}\ (\log_e \text{age})^7 + 1.708195 \times 10^{-16}\ (\log_e \text{age})^{22} - 2.482794 \times 10^{-22}\ (\log_e \text{age})^{30}.$$

Now that estimating equations are available for b_1 and HT and mean site index, $\bar{S} = 87.70$, is known, the equation is,

$\bar{S} - 4.5 = a_1 + \hat{b}_1\ (\hat{HT} - 4.5)$. Rearranged,

$\hat{a}_1 = \bar{S} - 4.5 - \hat{b}_1\ (\hat{HT} - 4.5)$.

The resulting $\hat{a}_1$ values are shown in table 2. The $\hat{a}_1$ and $\hat{b}_1$ values in table 2 can be used to estimate site index for combinations of height and age.

Substituting $\hat{a}_1$, $\hat{b}_1$, and $\hat{HT}$ into the basic equation,

$S - 4.5 \text{ feet} = a_1 + b_1(HT - 4.5 \text{ feet})$, gives

$S - 4.5 = \hat{a}_1 + \hat{b}_1\ (\hat{HT} - 4.5)$, and

$S - 4.5 = [\bar{S} - 4.5 - \hat{b}_1\ (\hat{HT} - 4.5)] + \hat{b}_1\ (HT - 4.5)$, and

$S - 4.5 = 83.20 - e^{x_1}e^{x_2} + e^{x_1}\ (HT - 4.5)$, and

$S = 87.70 - e^{x_1}e^{x_2} + e^{x_1}\ (HT - 4.5)$.

The above equation can be used in a calculator or computer to estimate site index for various combinations of height and age.

The final estimating equation fit the basic data well, and there was no correlation between residuals from the equation, and site or age. Deviations of the basic data regression points were evident beyond age 100 (fig. 8).

Height growth curves.—Construction of the height growth curves for western hemlock was similar to that used for the site index curves, except that the roles of total height and site index were reversed to:

$HT - 4.5 \text{ feet} = c_1 + d_1\ (S - 4.5 \text{ feet})$.

Linear regressions of the basic data for western hemlock were calculated for each decade between 10 and 150 years (table 6).

Figure 8.—Site index curves for unmanaged, even-aged western hemlock in southeast Alaska. Dashed lines connect decadal points derived from the unsmoothed basic data regressions of $(S - 4.5 \text{ feet}) = a_1 + b_1 (HT - 4.5 \text{ feet})$. Solid lines represent smooth curves from a rearrangement of the estimating equation.

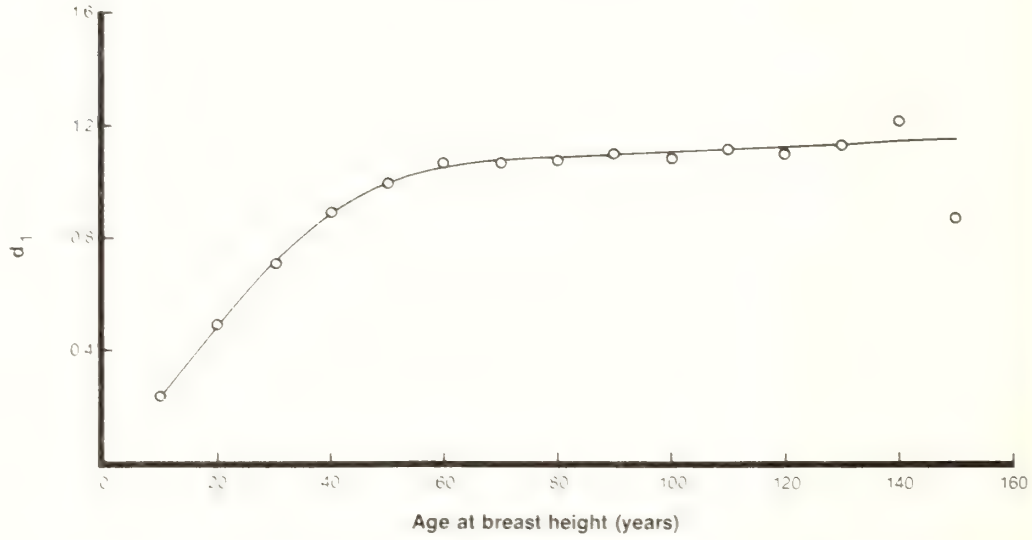


Figure 9.—d_1 values for western hemlock in the equation $(HT - 4.5 \text{ feet}) = c_1 + d_1 (S - 4.5 \text{ feet})$ as a function of age. Plotted points are actual d_1 values. Solid line is a curve expressed by the equation $\hat{d}_1 = e^{x_3}$, where x_3 is defined in the text. Standard error is 0.0156 and r^2 is 0.9974

The d_1 values were then smoothed over age (fig. 9). Coefficient d_1 turned upward at age 140 years, then sharply downward at age 150 because there were few observations in these age classes. This led to a distorted curve at upper ages, so an adjustment was made to smooth the curve at ages 140 and 150 years. Otherwise, the final height growth curves would be distorted at the upper ages.

The derived equation was:

$$\begin{aligned} x_3 = \log_e(\hat{d}_1) = & -2.146617 - 0.109007\ (\log_e age) \\ & + 0.0994030\ (\log_e age)^3 \\ & - 0.003853396\ (\log_e age)^5 \\ & + 1.193933 \times 10^{-8}\ (\log_e age)^{12} \\ & - 9.486544 \times 10^{-20}\ (\log_e age)^{27} \\ & + 1.431925 \times 10^{-26}\ (\log_e age)^{36}. \end{aligned}$$

The resulting $\hat{d}_1$ values are shown in table 4.

Substituting mean site index, ($\bar{S} = 87.70$, into the basic equation, $\hat{H}T - 4.5$ feet $= c_1 + \hat{d}_1\ (\bar{S} - 4.5$ feet), and rearranging, gives

$$\hat{c}_1 = (\hat{H}T - 4.5 - \hat{d}_1\ (87.70 - 4.5).$$

Values for $\hat{c}_1$ are given in table 4. The $\hat{c}_1$ and $\hat{d}_1$ values in table 4 can be used to estimate at any age total height of the average among the 40 largest diameter trees per acre, on land of known site index.

Substituting $\hat{c}_1$, $\hat{d}_1$, and $\hat{H}T$ into the basic equation,

$HT - 4.5$ feet $= c_1 + d_1\ (S - 4.5$ feet), gives

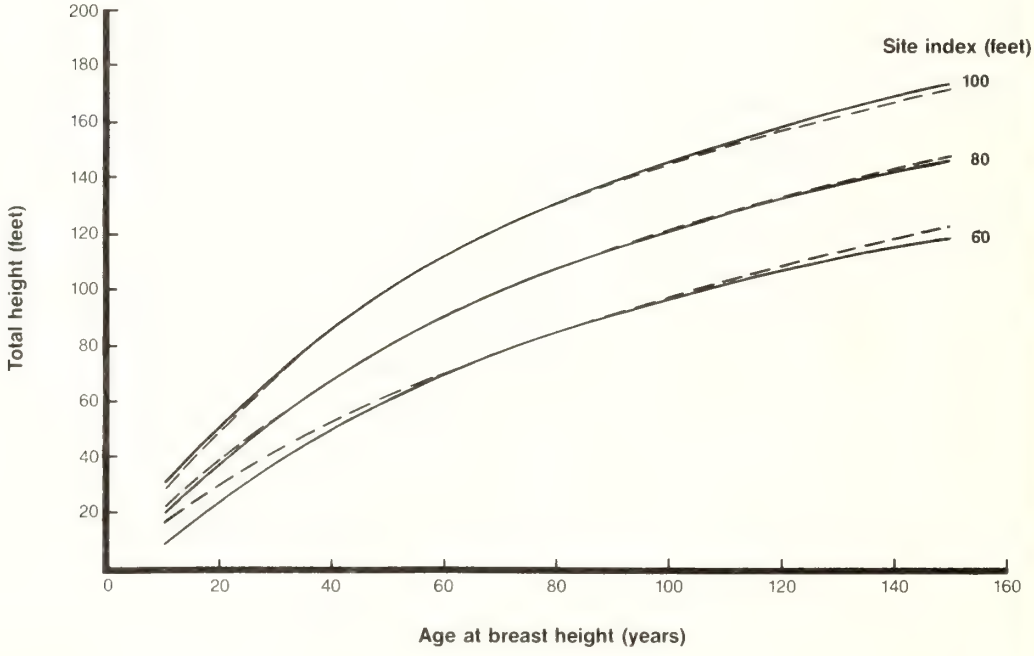
$$\begin{aligned} HT - 4.5 &= \hat{c}_1 + \hat{d}_1\ (S - 4.5), \text{ and} \\ HT - 4.5 &= [\hat{H}T - 4.5 - \hat{d}_1\ (\bar{S} - 4.5)] + \hat{d}_1\ (S - 4.5), \text{ and} \\ HT - 4.5 &= e^{x_2} - e^{x_3}\ (87.70 - 4.5) + e^{x_3}\ (S - 4.5), \text{ and} \\ HT &= 4.5 + e^{x_2} - e^{x_3}\ (83.20) + e^{x_3}\ (S - 4.5). \end{aligned}$$

The above equation can be used in a calculator or computer to estimate total height of the average among the 40 largest diameter trees per acre on land of known site index. Height growth curves for hemlock are shown in figure 10.

A graphic comparison between the site index and height growth curves for western hemlock is shown in figure 11.

Figure 10.—Height growth curves for unmanaged, even-aged western hemlock in southeast Alaska. Dashed lines connect decadal points derived from the unsmoothed basic data regressions of (HT − 4.5 feet) = $c_1 + d_1$ (S − 4.5 feet). Solid lines represent smooth curves from the estimating equation. Heights represent the means among the 40 largest diameter trees per acre.

Figure 11.—Site index (solid lines) and height growth curves (dashed lines) for unmanaged, even-aged western hemlock in southeast Alaska.



Construction of Curves for Sitka Spruce

Site index curves.—The same general procedures were used to construct the site index curves for Sitka spruce as were used to construct the site index curves for western hemlock. Linear regressions for the relationship $(S - 4.5 \text{ feet}) = a_2 + b_2 (HT - 4.5 \text{ feet})$ were calculated for each decade from 10 to 150 years. They were:

Age at breast height	a_2	b_2	r^2	Standard error of the estimate	Observations
(Years)	(Feet)	(Feet)		(Feet)	(Number)
10	43.3181	2.3233	0.57	10.64	71
20	27.2889	1.5085	.77	7.75	71
30	16.8460	1.2048	.88	5.53	71
40	9.0134	1.0487	.96	3.21	71
50	0	1.000	1.00	0	71
60	-.7774	.8890	.99	1.86	36
70	-2.1011	.8199	.96	2.99	30
80	-4.5038	.7850	.95	3.30	29
90	-6.3957	.7523	.94	3.74	26
100	-7.2216	.7192	.92	4.42	23
110	-6.8901	.6900	.87	4.45	19
120	-8.7211	.6766	.89	4.17	15
130	-8.7727	.6572	.90	4.27	13
140	-5.2298	.6153	.93	3.75	10
150	-1.7375	.5722	.92	4.08	8

Coefficient b_2 dipped downward beyond age 130 (fig. 12). This led to a poor fit of the combined equation at upper ages, so the curve of b_2 over age was adjusted to avoid distorted site index curves beyond 130 years.

The derived equation was:

$$\begin{aligned} x_4 - \log_e(\hat{b}_2) = {} & 6.396816 - 4.098921 (\log_e \text{age}) \\ & + 0.7628741 (\log_e \text{age})^2 \\ & - 0.00244688 (\log_e \text{age})^5 \\ & + 2.445811 \times 10^{-7} (\log_e \text{age})^{10} \\ & - 2.022153 \times 10^{-22} (\log_e \text{age})^{30}. \end{aligned}$$

Mean height minus 4.5 feet for each 10-year age at breast height was also calculated (table 7 and fig. 13). Number of plots and mean site index in each 10-year age decreased beyond age 50, so mean height beyond age 50 did not reflect the correct height for mean site 90.93. Heights were then adjusted by use of the c_2 and d_2 coefficients for each age class and mean site index at age 50 in the equation,

$$HT = 4.5 + c_2 + d_2 (90.93 - 4.5).$$

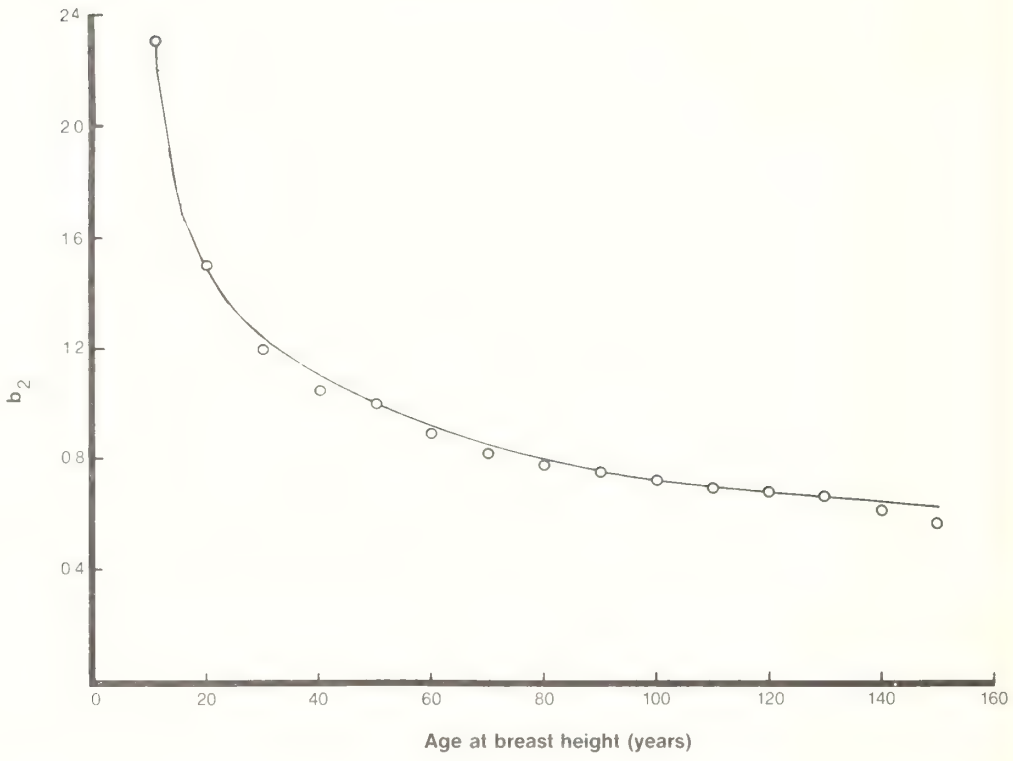


Figure 12.—b_2 values for Sitka spruce in the equation $(S - 4.5 \text{ feet}) = a_2 + b_2 (HT - 4.5 \text{ feet})$ as a function of age. Solid line is expressed by the equation $\hat{b}_2 = e^{x_4}$. Coefficient x_4 is defined in the text. Standard error is 0.0008 and r^2 is 0.9959.

Table 7—Regression coefficients for Sitka spruce from the equation (height − 4.5) = c_2 + d_2 (site − 4.5) by 10-year age class, and corrections for mean height after age 50, southeast Alaska

Age at breast height	c_2	d_2	r^2	Standard error of estimate	Observations	Mean height	Corrected	
							Mean height 1/	Adjusted mean height 2/
Years				Feet	Number	- - - - - - - Feet- - - - - - -		
10	-2.5912	0.2447	0.57	3.45	71	23.06	23.06	23.06
20	-4.9658	.5110	.77	4.51	71	43.70	43.70	43.70
30	-5.6386	.7334	.88	4.31	71	62.25	62.25	62.25
40	-5.3580	.9161	.96	3.00	71	78.32	78.32	78.32
50	0	1.0000	1.00	0	71	90.93	90.93	90.93
60	2.1197	1.1090	.99	2.08	36	93.61	102.47	102.47
70	6.4509	1.1680	.96	3.57	30	98.90	111.90	111.90
80	10.6176	1.2088	.95	4.10	29	105.59	119.59	119.59
90	14.4174	1.2503	.94	4.82	26	112.69	126.98	126.98
100	18.4553	1.2779	.92	5.90	23	118.43	133.40	133.40
110	24.5582	1.2631	.87	6.02	19	127.95	138.23	138.23
120	29.3460	1.2537	.89	5.49	15	130.07	142.20	144.90
130	24.8464	1.3724	.90	6.17	13	135.08	147.96	148.73
140	18.1998	1.5044	.93	5.86	10	143.50	152.73	151.99
150	14.9222	1.6006	.92	6.82	8	148.88	157.76	154.75

1/ After age 50, heights were calculated from the equation height = 4.5 + c_2 + d_2 (90.93 - 4.5) to adjust for decreasing numbers of observations and changing mean site index.

2/ Values actually used to compute coefficients in the height over age equation. They were derived by fitting the basic data to a nonlinear equation for HT = f(site, age), then solving for mean site index 90.93 to estimate smoothed mean heights for ages 120 to 150 years.

Figure 13.—Mean height of sectioned Sitka spruce as a function of age at breast height for each 10-year age class. Plotted points are actual mean heights minus 4.5 feet. Solid line is expressed by the equation $(\hat{HT} - 4.5 \text{ feet}) = e^{x_5}$, where x_5 is defined in the text Standard error is 0.094 and r^2 is 0.99995.

Even then there were problems at upper ages because of scarcity of observations. This caused a biased fit of the combined equation at 120 to 150 years. The problem was later corrected by fitting the basic data to a combined nonlinear equation for HT = f(S, A), then solving for mean site index 90.93 to estimate smoothed mean heights for ages 120 to 150. This avoided any correlation between the residuals and site and age.

The derived equation was:

$$x_5 = \log_e(\hat{HT} - 4.5 \text{ feet} = -0.2050542 + 1.449615\ (\log_e \text{age}) - 0.01780992\ (\log_e \text{age})^3 + 6.519748 \times 10^{-5}\ (\log_e \text{age})^5 - 1.095593 \times 10^{-23}\ (\log_e \text{age})^{30}.$$

Now that estimating equations are available for b_2 and HT and mean S = 90.93 is known, the equation is,

$\bar{S} - 4.5 = a_2 + \hat{b}_2\ (\hat{HT} - 4.5)$. Rearranged,

$\hat{a}_2 = \bar{S} - 4.5 - \hat{b}_2\ (\hat{HT} - 4.5)$.

The resulting $\hat{a}_2$ values are those shown in table 3. The $\hat{a}_2$ and $\hat{b}_2$ values in table 3 can be used to estimate site index for combinations of height and age.

Substituting $\hat{a}_2$, $\hat{b}_2$, and $\hat{H}T$ into the basic equation,

$S - 4.5$ feet $= a_2 + b_2(HT - 4.5$ feet), gives

$$S - 4.5 = \hat{a}_2 + \hat{b}_2 (\hat{H}T - 4.5), \text{ and}$$

$$S - 4.5 = [\bar{S} - 4.5 - \hat{b}_2 \ (\hat{H}T - 4.5)] + \hat{b}_2 (HT - 4.5), \text{ and}$$

$$S - 4.5 = 86.43 - e^{x_4}e^{x_5} + e^{x_4} (HT - 4.5), \text{ and}$$

$$S = 90.93 - e^{x_4}e^{x_5} + e^{x_4} (HT - 4.5).$$

The above equation can be used in a calculator or computer to estimate site index for various combinations of height and age. The site index curves are shown in figure 3.

The final estimating equations fit the basic data regression points well. Deviations were evident beyond age 120 (fig. 14).

Height growth curves.—Construction of the height growth curves for Sitka spruce was similar, except the roles of total height and site index were reversed to,

$HT - 4.5$ feet $= c_2 + d_2 (S - 4.5$ feet).

Linear regressions of the basic data for Sitka spruce were calculated for each decade between 10 and 150 years (table 7).

The d_2 values were then smoothed over breast high age (fig. 15). Coefficient d_2 turned sharply upward beyond age 120 as there were few observations in the upper age classes. This led to a poor fit of the combined equation beyond age 120, so the curve of d_2 was, by trial and error, subjectively smoothed for ages greater than 120 years so that the height growth curves could be extended to age 150.

The derived equation was:

$$\begin{aligned} x_6 = \log_e(\hat{d}_2) = \ & - 5.6118790 + 2.418604 (\log_e \text{age}) \\ & - 0.259311 (\log_e \text{age})^2 \\ & + 1.351445 \times 10^{-4} (\log_e \text{age})^5 \\ & - 1.701139 \times 10^{-12} (\log_e \text{age})^{16} \\ & + 7.964197 \times 10^{-27} (\log_e \text{age})^{36}. \end{aligned}$$

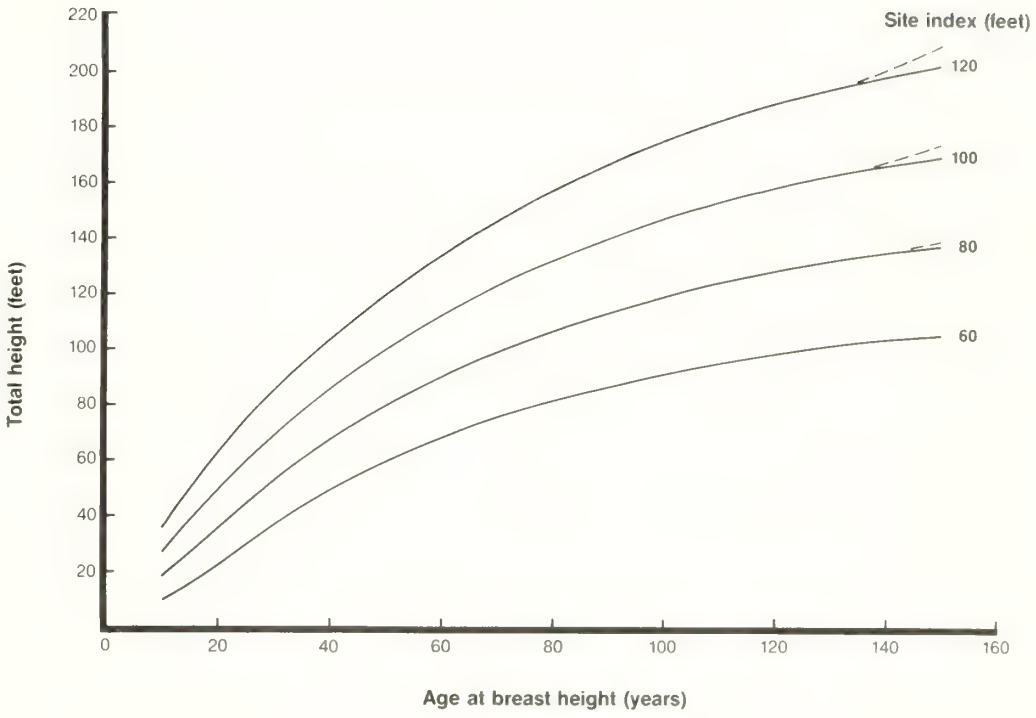
The resulting $\hat{d}_2$ values are shown in table 5.

Substituting mean site index $\bar{S} = 90.93$ into the basic equation,

$\hat{H}T - 4.5$ feet $= c_2 + \hat{d}_2 (\bar{S} - 4.5$ feet), and rearranging, gives

$$\hat{c}_2 = \hat{H}T - 4.5 - \hat{b}_1(\bar{S} - 4.5).$$

igure 14.—Site index curves or unmanaged, even-aged itka spruce in southeast laska. Dashed lines connect ecadal points derived from ne unsmoothed basic data egressions of (S − 4.5 feet) = $_2$ + b_2 (HT − 4.5 feet). Solid nes represent smooth curves om a rearrangement of the stimating equation.



igure 15.—d_2 values for Sitka pruce in the equation (HT − .5 feet) = c_2 + d_2 (S − 4.5 eet) as a function of age. lotted points are actual d_2 alues. Solid line is a curve xpressed by the equation $\hat{d}_2$ = e^{x_6}, where x_6 is defined in ne text. Standard error is 0.008 nd r^2 is 0.9921.

Values for $\hat{c}_2$ are given in table 5. The $\hat{c}_2$ and $\hat{d}_2$ values in table 5 can be used to estimate at any age total height of the average among the 40 largest diameter trees per acre on land of known site index.

Substituting $\hat{c}_2$, $\hat{d}_2$, and $\hat{HT}$ into the basic equation,

$$HT - 4.5 \text{ feet} = c_2 + d_2 (S - 4.5 \text{ feet}), \text{ gives}$$

$$HT - 4.5 = \hat{c}_2 + \hat{d}_2 (S - 4.5), \text{ and}$$

$$HT - 4.5 = [\hat{HT} - 4.5 - \hat{d}_2 (\bar{S} - 4.5)] + \hat{d}_2 (S - 4.5), \text{ and}$$

$$HT - 4.5 = e^{x_5} - e^{x_6} (90.93 - 4.5) + e^{x_6} (S - 4.5), \text{ and}$$

$$HT = 4.5 + e^{x_5} - e^{x_6} (86.43) + e^{x_6} (S - 4.5).$$

The above equation can be used in a calculator or computer to estimate total height of the average among the 40 largest trees per acre on land of known site index. Height growth curves for Sitka spruce are shown in figure 16.

A graphic comparison between the site index and height growth curves for Sitka spruce is shown in figure 17.

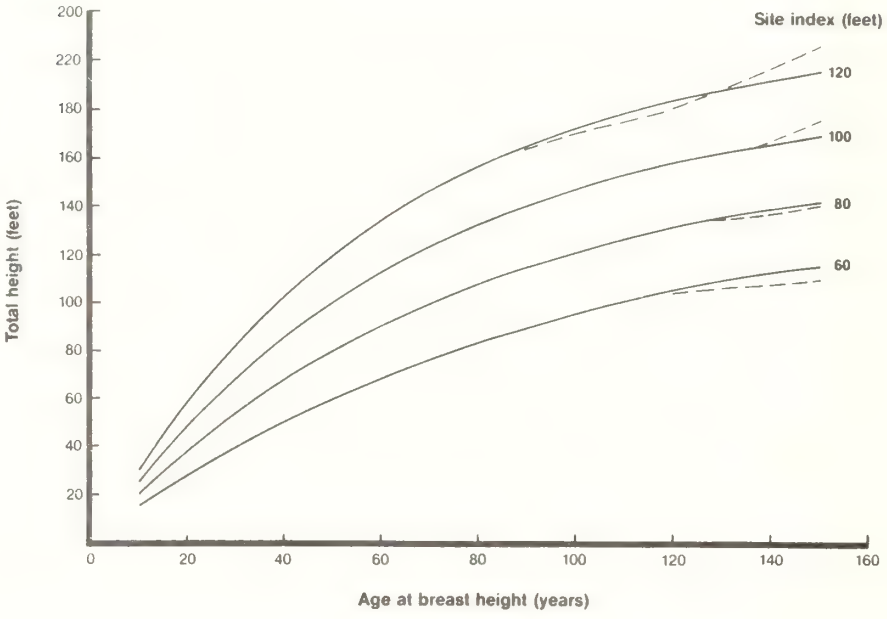


Figure 16.—Height growth curves for unmanaged, even-aged Sitka spruce in southeast Alaska. Dashed lines connect decadal points derived from the unsmoothed basic data regressions of (HT − 4.5 feet) = $c_2 + d_2$ (S − 4.5 feet). Solid lines represent smooth curves from the estimating equation. Heights represent the mean among the 40 largest diameter trees per acre.

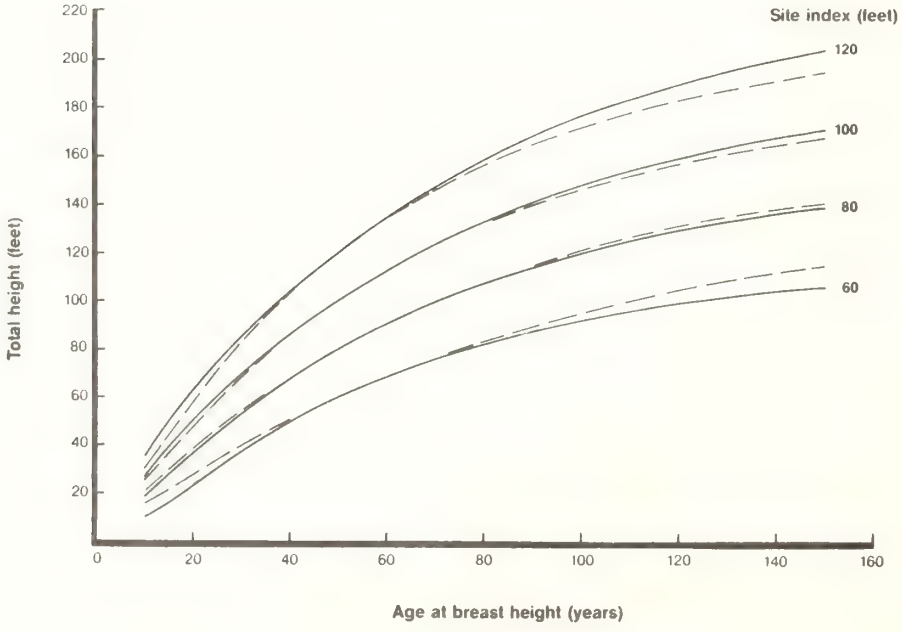


Figure 17.—Site index (solid lines) and height growth curves (dashed lines) for unmanaged, even-aged Sitka spruce in southeast Alaska.

Farr, Wilbur A. Site index and height growth curves for unmanaged even-aged stands of western hemlock and Sitka spruce in southeast Alaska. Res. Pap. PNW-326. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1984.** 26 p.

Height growth and site index curves and equations are presented for unmanaged even-aged stands of western hemlock and Sitka spruce in southeast Alaska. Data were mostly collected in stands that developed after logging.

Keywords: Even-aged stands, site index, increment (height), stem analysis, western hemlock, *Tsuga heterophylla,* Sitka spruce, *Picea sitchensis,* southeast Alaska, Alaska (southeast).

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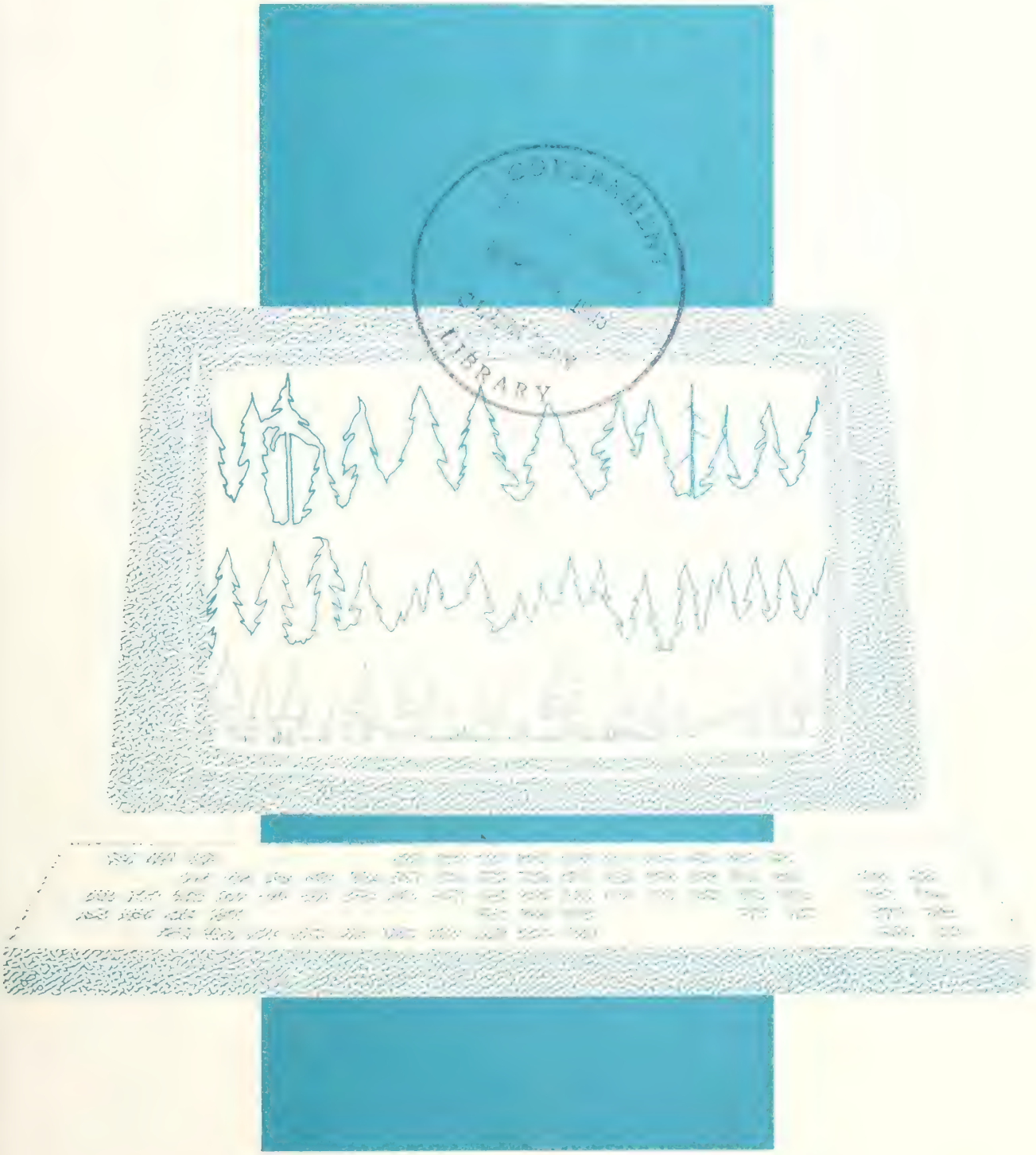
Research Paper
PNW-327
December 1984

CLIMACS: A Computer Model of Forest Stand Development for Western Oregon and Washington

Virginia H. Dale and Miles Hemstrom



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Abstract

Dale, Virginia H.; Hemstrom, Miles. CLIMACS: A computer model of forest stand development for western Oregon and Washington. Res. Pap. PNW-327. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1984.** 60 p.

A simulation model for the development of timber stands in the Pacific Northwest is described. The model grows individual trees of 21 species in a 0.20-hectare (0.08-acre) forest gap. The model provides a means of assimilating existing information, indicates where knowledge is deficient, suggests where the forest system is most sensitive, and provides a first testing ground for hypotheses. Model verification simulations are included for up to 500 years on various sites. Fire, wind, or clearcutting can occur at intervals and intensities specified by users. The model was developed by modifying an existing forest succession simulator of eastern deciduous forests. Birth, growth, and death of individual trees are functions of existing light and temperature conditions, competition and species characteristics. Modifications of the existing simulator include tree height growth being related to temperature and moisture conditions, the foliage biomass to diameter relationship being more realistic, and five mortality classes and shade tolerance classes being defined.

Keywords: Succession, models, simulation, community dynamics (plant).

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Introduction

CLIMACS (Computer Linked Integrative Model for Assessing Community Structure) is a simulation model of forest succession for western Oregon and Washington. The model tracks characteristics of individual trees growing in a forest opening of 0.20 hectare (0.08 acre). The FORTRAN IV code of CLIMACS is based on FORET (Shugart and West 1977), a succession model for eastern Tennessee, which in turn was modified from JABOWA (Botkin and others 1972), a simulator for forests of the northeastern United States. CLIMACS retains the stochastic features of the succession models for the eastern deciduous forests and has a more elaborate diameter increment equation and treatment of mortality. A moisture stress index is incorporated into the function that calculates diameter increment, and height growth is dependent upon site quality for some species. Mortality is related to the size of the tree and the successional status of the species under consideration. Three types of disturbance can occur: fire, wind, or clearcuts.

The model paradigm represents our view of succession as the result of individual tree processes and episodic disturbances. The term "climax" is tenuous because pioneer species are so long-lived that climax forests rarely develop in the Pacific Northwest even though major disturbances are infrequent. Although the simulator should be realistic enough to approximate stand development on particular sites, its main value is in summarizing and testing current hypotheses about tree growth and the factors affecting succession. The model is an exercise that should be useful to managers to examine hypotheses of the long-term effects of human activities on stand development.

A review of forest succession models is presented by Shugart and West (1980). According to their terminology, CLIMACS is a gap model that simulates characteristics of individual trees in a small portion of the forest—either an opening in the canopy or a sample plot. Such models are particularly useful for evaluation of long-term and large-scale changes in the environment and the effects of those changes on forest succession.

The purpose of this paper is to clarify algorithms and subroutines of the model. The basic features of the model are described in Botkin and others (1972) and Shugart and West (1977). Following the standards for model documentation from Swartzman (1979), the assumptions of the model are set forth, the value and source of each parameter is given, the source of the equations and potential problems of the curve forms are indicated, and the logic of the FORTRAN program is presented. This paper describes the structure of the main program and discusses the four major subroutines: BIRTH, GROW, KILL, and DISTRB. Results for several forest sites are presented.

The model code is stored on computer tape at the Forest Science Data Bank, Department of Forest Science, Oregon State University, Corvallis, Oregon.

Table 1—State variables[1]

Name	Definition	Units	Subroutines
A(KYR,i)	Aboveground biomass for species	t/ha	MAIN, OUTPUT, PLTREE
A(KYR, NSPEC+2)	Total number of trees per plot		
A(KYR, NSPEC+3)	Leaf area index for plot	m^2/m^2	PLTREE, OUTPUT, MAIN
A(KYR, NSPEC+1)	Stand biomass	t/ha	
DBH(j)	Diameter at breast height of tree j	cm	SPROUT, KILL, GROW, OUTPUT, BIRTH
IAGE(k)	Age of tree k	yrs	GROW, KILL, SPROUT
NTREES(i)	Number of trees of species i		SPROUT, GROW
BIOM	Stand biomass = A(KYR,i)	t/ha	PLTREE
BAREA	Basal area of stand	m^2/ha	PLTREE
A(KYR1, 26)	Total foliage biomass	t/ha	OUTPUT, PLTREE
FB(i)	Foliage biomass for species	t/ha	OUTPUT, PLTREE
D(i,k)	Number of stems of species i in diameter class (k*10) to (k*10 + 10)		PLTREE

[1]Numbers that represent the current state or condition of the system.

Structure and Assumptions

The model updates and records on an annual basis characteristics of all individual trees greater than 10 cm diameter at breast height (d.b.h.) on a 0.20-hectare (0.08-acre) plot (table 1). In the model, foliage is distributed vertically but not horizontally (Cartesian coordinates of each tree are not recorded). The driving variables (numbers that are inputs to the model and are not affected by the components of the system) for the model are plant moisture stress (PMS) (-bars) and temperature growth index (TGII) (days). PMS is the predawn negative xylem pressure measured near the end of the growing season (Waring and Cleary 1967). TGII is from a temperature summation formula that weighs temperatures by their effects on the production of seedlings of *Pseudotsuga menziesii* (Mirb.) Franco (Cleary and Waring 1969). In the model, the yearly temperature growth index (TGI) varies from year to year in a normal distribution around the driving variable TGII. The model has six major assumptions:

1. PMS and TGII reflect the main physical driving variables of forest succession.
2. Competition for light is the primary biological factor affecting forest succession.
3. Regeneration of species that can grow under existing light and soil conditions is stochastic within the bounds of the geographic distribution of the species.
4. Diameter increment can be modeled as a multiplicative function of tree size, photosynthetic rate as reflected in foliage biomass, nutrient competition, light availability, shade tolerance, and moisture and temperature stress.
5. Mortality can occur at two levels—an individual tree and a portion of the stand.
6. Individual tree mortality is conditioned by growth rate.

A listing of the entire program is given in Appendix 1.

The model can be applied to four geographic regions west of the Cascade Range: Santiam Pass south to the California border, Santiam Pass north to Mount Rainier, north of Mount Rainier to the Canadian border, and the Olympic Peninsula (fig. 1). Restriction of a model run to a geographic region limits the species in the succession model to those found naturally in the region.

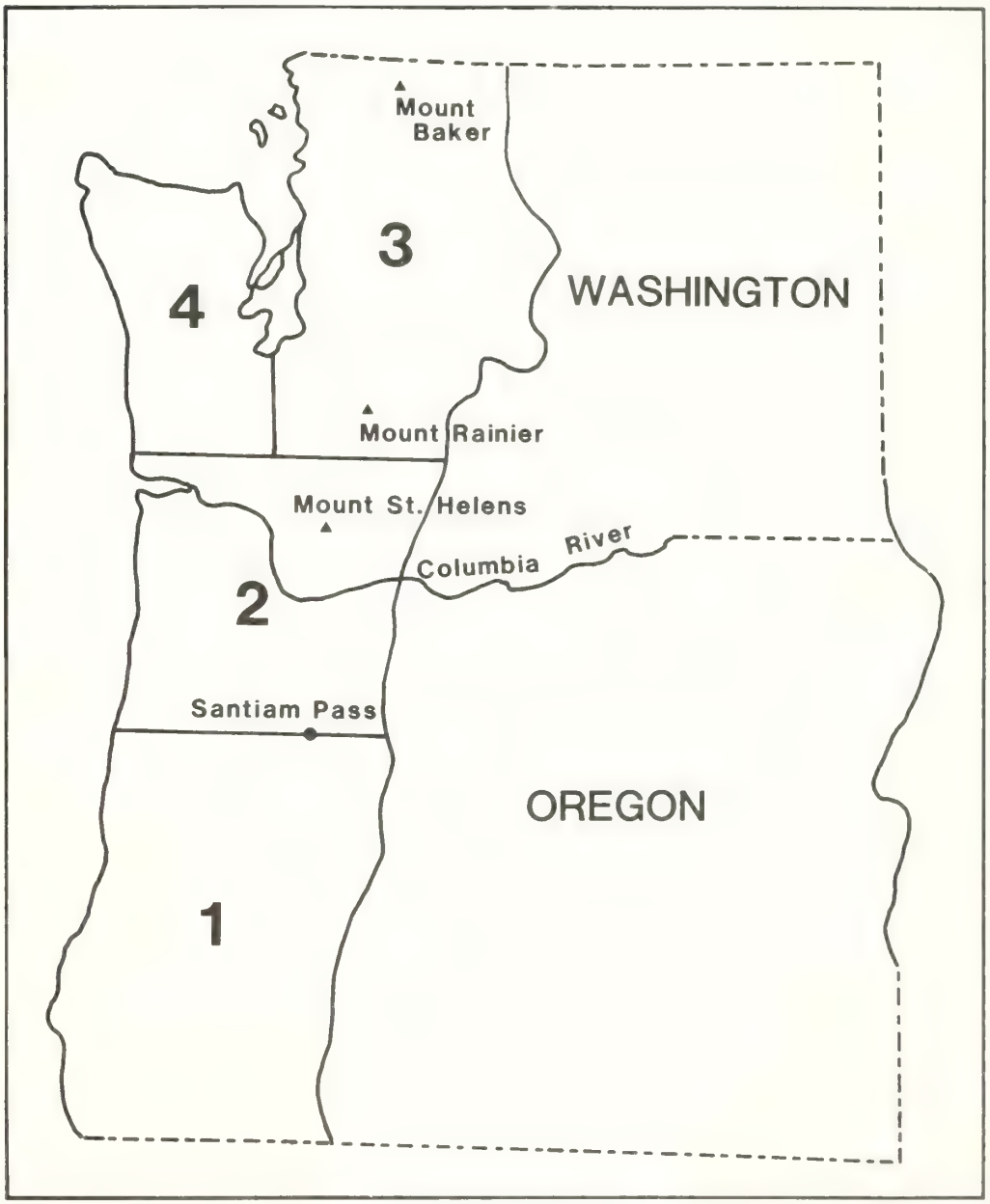

Figure 1.—The model is applicable to four geographic regions in Oregon and Washington.

Main Program

The main program manages the entire model by initializing the year and plot replicate counters, setting the data storage array to zero, and calling the major subroutines as outlined in figure 2. A successional sequence can occur on replicate plots and for as many years as specified by the user. The model can start from a bare plot (see subroutine BIRTH), or the user can read in the species and diameter of each tree on the plot (see subroutine INPUT). The names and parameters of the species, driving variables, and length of the model run are read in by a call from the main program to subroutine INPUT. For each year of the simulation the appropriate species for the site are selected (subroutine SELECT), trees can die (subroutine KILL), regeneration occurs (subroutine BIRTH), and the diameter of

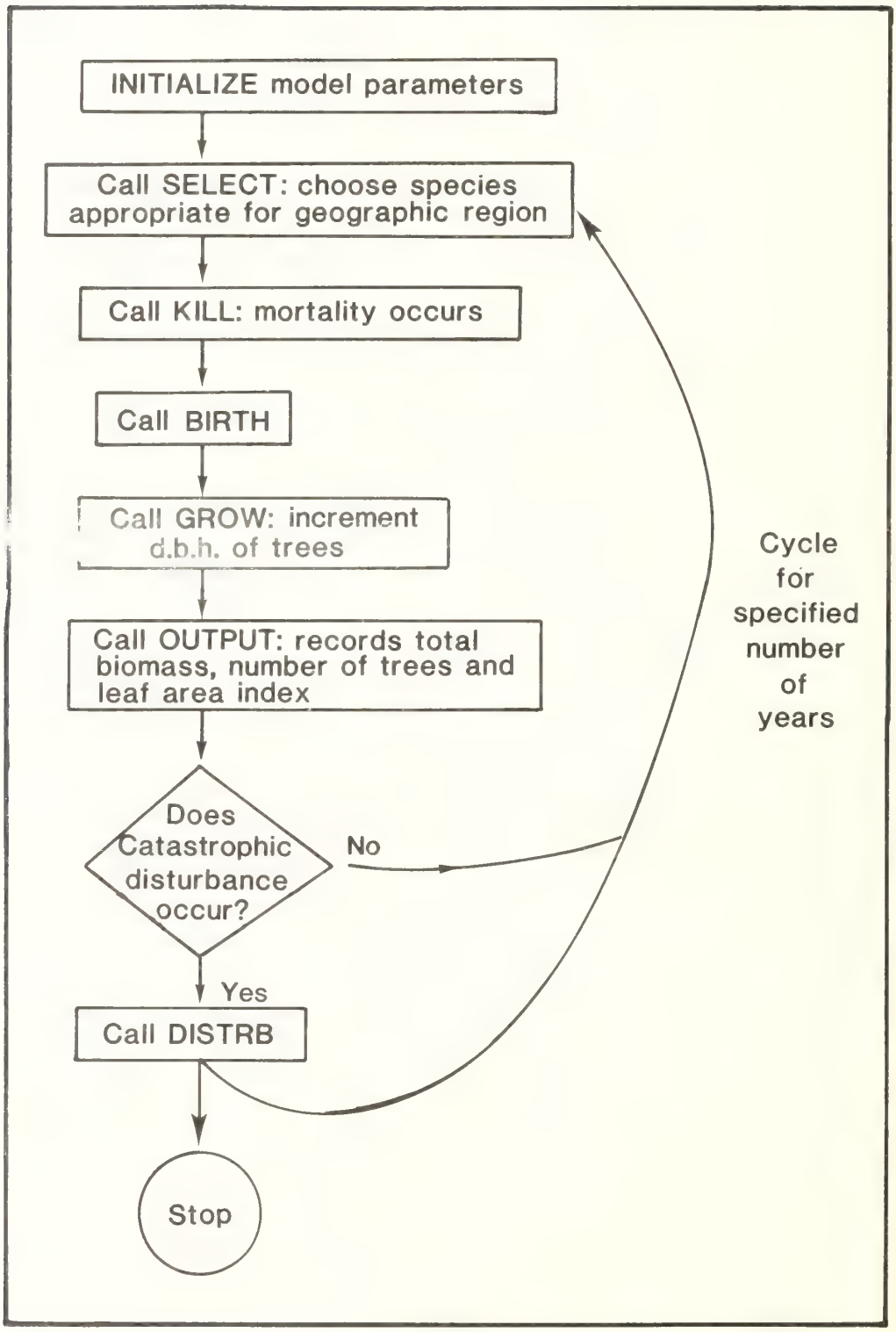
INITIALIZE model parameters
Call SELECT: choose species appropriate for geographic region
Call KILL: mortality occurs
Call BIRTH
Call GROW: increment d.b.h. of trees
Call OUTPUT: records total biomass, number of trees and leaf area index
Does Catastrophic disturbance occur?
No
Yes
Call DISTRB
Stop
Cycle for specified number of years

Figure 2.—General scheme of model.

Table 2—Subroutines

Subroutine	Discussion
BIRTH(KYR)	Introduces new trees with the diameter randomly distributed between 10 and 15 cm at breast height of the tree. KYR = current year.
ERR	Indicates error when there are more than 700 trees per plot.
GGNORD (NSEED1, NSEED2, Z)	Provides a normal distribution, Z, based on the random numbers NSEED1 and NSEED2.
GROW	Growth of d.b.h. and leaf area.
INIT	NOGRO(I) = 0, I = 1, 700; KSPRT(I) = 1, I = 1, NSPEC.
INPUT	Reads and writes species specific names and parameters.
KILL	Eliminates trees as a function of diameter and growth rate.
OUTPUT	Updates biomass and the leaf area index.
PLOTIN(IPLOT)	Variables to start simulation in a bare plot (IPLOT = plot number).
PLTREE	Writes out information on species and years.
RANDOM(NSEED)	Random number generator (NSEED = seed).
RANSEE	Reads random number generator seed from input file.
SELECT	Checks water stress and temperature requirements for species in the four geographic regions.
SPROUT	Stump sprouting for appropriate species.

existing trees increases (subroutine GROW). A discussion of each subroutine is given in table 2. For specified years, stand and species characteristics are printed out in tabular form (see Appendix 2).

Definitions of the constants, indices, and parameters are given in tables 3, 4, 5, and 6. The parameter values are appropriate for species in the Pacific Northwest and their sources are indicated in tables 7, 8 and 9.

Table 3—Constants

Name	Value	Definition	Units	Subroutines
soilq	100000.0	Maximum biomass for forests in the area	kg/ha	GROW, MAIN
size	10.0	Mean d.b.h. of new trees	cm	SPROUT, BIRTH
PI2	6.283	2π		GGNORD
phi	1.0	Proportion of annual light attenuation constant		GROW
tinc	.1	Minimum growth of d.b.h. per year to trigger mortality	cm	GROW

Table 4—Indexes

Index	Range	Meaning
i	1 - NSPEC	Species of tree
j	1 - NTOT	Individual tree
KYR	1 - NYEAR	Model year
IPLOT	1 - total number of plots	Plot number

Table 5—Parameters

Name	Definition	Units	Source of values or relationships	Subroutines
AAA(i,j)	Array of species names			KILL, GROW, INPUT
$A_1(i)$	Intercept for stemwood	kg	Gholz and others (1979)	KILL, INPUT, GROW, OUTPUT
$A_2(i)$	Intercept for the foliage	kg	Gholz and others (1979)	KILL, INPUT, GROW,
AL[1]	Available light		(See GROW)	GROW
AREA[1]	Total leaf area	m^2/m^2	(See OUTPUT)	OUTPUT
ATOT[1]	Total number of trees in plot		(See OUTPUT)	OUTPUT
BAR(i)[1]	Total aboveground wood and foliage biomass	t/ha	Gholz and others (1979)	OUTPUT
BB(i)	Slope for stemwood biomass		Gholz and others (1979)	INPUT, KILL, GROW, OUTPUT
BC(i)	Slope for total foliage biomass equation		Gholz and others (1979)	OUTPUT, KILL, GROW, INPUT
$B_1(i)$	Coefficient relating tree volume growth to leaf biomass		Reed and Clark (1979)	INPUT
$B_2(i)$[1]	Height parameter		Botkin and others (1972) (calculated from DBHMX and HMAX) (see GROW)	BIRTH, INPUT, KILL, GROW
$B_3(i)$[1]	Height parameter			
$B_4(i)$	Exponential relating tree volume growth to leaf biomass		Reed and Clark (1979)	INPUT
C(i)	Conversion from leaf mass to area	m^2/kg	Gholz and others (1979)	KILL, GROW, INPUT
DBHMX	Maximum diameter at breast height	cm	Franklin and Dyrness (1973)	KILL, GROW, INPUT
DMAX(i)	Maximum number of degree growing days	days	Emmingham and Waring (Personal communication)	KILL, SELECT, GROW, INPUT
DNC[1]	Diameter increment shading and competition	cm	Modified from Botkin and others (1972) (see GROW)	GROW
FBIO[1]	Total foliage biomass	kg	Gholz and others (1979)	GROW, OUTPUT, BIRTH
FI	Fire intensity ($0 \leq FI \leq 1$)			DISTRB
HMAX(i)	Maximum height of species i	dm	See Table 7	INPUT
HT[1]	Tree height	dm	(See GROW)	GROW
IGEOG	Geographic region			INPUT, GROW, SELECT, KILL
IHT[1]	Decimeter height class for trees		(See GROW)	GROW
IREG(j,IGEOG)	Indicates species availability in geographic region IGEOG			KILL, SELECT, BIRTH, INPUT
ISEL(i)	Summarizes whether species can occur in a region			KILL, SELECT, BIRTH, GROW
ITOL(i)	Indicates shade tolerance		(See GROW)	KILL, GROW, INPUT
MPLANT	Randomly chosen number of species to plant (0 to 8)			BIRTH
NCODE(i)	Species code number			BIRTH, GROW, SPROUT, OUTPUT, KILL, PLTREE
NTOT	Total number of trees in plot			KILL, SPROUT, GROW, OUTPUT, BIRTH
P	Probability a tree survives a disturbance (wind or fire)		(See DISTRB)	DISTRB
PR	Probability a tree species survives 1 year of slow growth		(See KILL)	KILL
NSPRT	Randomly selected number of trees to sprout			BIRTH, SPROUT
SBIO[1]	Total foliage biomass and stem wood biomass (without bark) except for alder	t/ha	Gholz and others (1979) (See GROW)	GROW
SLAR	Shading leaf area, leaf above that of size (dm) of tree	m^2/m^2	(See GROW)	GROW
SPNAM(i)	Alphanumeric species names being considered			
SPRTMN(i)	Minimum d.b.h. for sprouting to occur	cm		KILL, GROW, INPUT
SPRTMX(i)	Maximum d.b.h. for sprouting	cm	DBHMX except for alder	KILL, GROW, INPUT
SPRTND(i)	Average number of sprouts on death of main stem			SPROUT, KILL, GROW, INPUT
SUMLA(IHT)	Sum of leaf area of trees in dm size class IHT (latter of all dm classes)	m^2/m^2		GROW
WMIN(i)	Minimum value of water stress	bars		SELECT, GROW, KILL, INPUT
WATDEX[1]	Moisture index		(See GROW)	GROW
Z(k)[1]	Normal distribution		(See GGNORD)	GROW, GGNORD

[1]Calculated parameters.

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Table 6—Internal parameters[1]

Name	Definition	Subroutine
KSPRT(i)	= -1 if sprouting occurs = 1 if no sprouts	KILL, SPROUT, INIT
KLAST	=KTIMES, current iteration	MAIN
KYR	Current year (0 KYR NYEAR)	MAIN
NCT	Keeps track of number of years in the main program	MAIN
KYR1	KYR = 1	MAIN, OUTPUT, BIRTH
NG	Number of trees not growing	KILL, GROW
N1	NSPEC + 1	OUTPUT
N2	NSPEC + 2	OUTPUT, NSPC
NSPC	Species to sprout iteration	SPROUT
NUM	Species number (1 = NUM = NSPEC)	INPUT
NSP	Randomly selected species to plant	BIRTH
NEW	Possible species to sprout	KILL, SPROUT
NEWTR	Species of possible new trees	KILL, GROW
NOGRO(i)	Equals 0 if tree is not growing	INIT, KILL, GROW
RANDOM	Random number	
RAT	Random number which is fixed for year	BIRTH
ZNYR	KLAST	MAIN

[1]Those that keep track of processes in the FORTRAN program itself.

Table 7—Parameter values for CLIMACS

Species	SPRTMN	SPRTMX[1]	KTIME	Growth Parameters[2] A1	A2	BB	BC	C	WMIN[3]
Abies amabilis	0	0	9999	-3.5057	-4.5490	2.5744	2.1926	15.2000	18
Abies grandis	0	0	9999	-3.7389	-3.4660	2.6825	1.9278	13.1000	18
Abies lasiocarpa	0	0	9999	-3.7389	-3.4660	2.6825	1.9278	13.2000	10
Abies procera	0	0	9999	3.7158	-4.8730	2.7592	2.1683	13.2000	18
Acer macrophyllum	10	50	9999	-3.4930	-3.7650	2.7230	1.6170	26.1000	18
Alnus rubra	10	75	9999	0	0	0	0	28.2000	8
Arbutus menziesii	10	120	9999	-3.7080	-3.1230	2.6580	1.6930	12.6000	30
Castanopsis chrysophylla	10	90	9999	-3.7080	-3.1230	2.6580	1.6930	12.6000	20
Chamaecyparis nootkatensis	0	0	9999	-2.0927	-2.6170	2.1863	1.7824	17.7000	10
Libocedrus decurrens	0	0	9999	-2.0927	-2.6170	2.1863	1.7824	17.7000	27
Picea engelmannii	0	0	9999	-3.7389	-3.4660	2.6825	1.9278	17.4000	8
Picea sitchensis	0	0	9999	-3.7389	-3.4660	2.6825	1.9278	17.4000	5
Pinus contorta	0	0	9999	-2.9849	-3.6190	2.4287	1.8362	17.4000	15
Pinus lambertiana	0	0	9999	-3.9840	-4.0230	2.6667	2.0327	17.4000	25
Pinus monticola	0	0	9999	-4.2847	-3.9740	2.7180	2.0039	17.4000	10
Pinus ponderosa	0	0	9999	-4.4907	-4.2610	2.7587	2.0967	17.4000	20
Pseudotsuga menziesii	0	0	9999	-3.0396	-2.8460	2.5951	1.7009	17.4000	25
Quercus garryana	10	90	9999	-3.4930	-3.1230	2.7230	1.6930	12.6000	25
Thuja plicata	0	0	9999	-2.0927	-2.6170	2.1863	1.7824	17.7000	10
Tsuga heterophylla	0	0	9999	-2.1720	-4.1300	2.2570	2.1280	20.4000	18
Tsuga mertensiana	0	0	9999	-4.8164	-3.8170	2.9308	1.9756	20.4000	10

[1]SPRTMX = DBHMX except for Alnus rubra which does not sprout from large trees.

[2]Gholz and others (1979).

[3]Zobel and others (1976), Waring (1969), and Waring, personal communication.

Table 8—Parameter values for moisture index

SPECIES	Degree Days		Height Parameters				
	Max.	Min.	B3	B2	ITOL	AGEMX	SPRTND
Abies amabilis	80	20	0.22	85.60	5	450	0
Abies grandis	100	50	.21	76.05	3	350	0
Abies lasiocarpa	60	20	.78	95.18	3	350	0
Abies procera	70	30	.19	68.29	2	450	0
Acer macrophyllum	115	85	.55	55.48	3	250	3
Alnus rubra	90	45	.54	81.68	2	150	3
Arbutus menziesii	130	75	.16	38.35	2	200	3
Castanopsis chrysophylla	130	60	.14	74.73	2	150	3
Chamaecyparis nootkatensis	60	20	.23	69.29	4	1500	0
Libocedrus decurrens	130	60	.30	72.72	4	750	0
Picea engelmannii	60	20	.46	92.94	2	650	0
Picea sitchensis	90	60	.14	64.03	3	450	0
Pinus contorta	70	20	.52	77.63	1	200	0
Pinus lambertiana	130	70	.34	85.81	3	450	0
Pinus monticola	70	40	.16	63.79	3	450	0
Pinus ponderosa	130	100	.38	93.81	1	650	0
Pseudotsuga menziesii	130	30	.23	80.44	2	1000	0
Quercus garryana	130	100	.29	52.51	1	350	3
Thuja plicata	90	45	.23	64.71	4	750	0
Tsuga heterophylla	95	35	.27	81.21	5	600	0
Tsuga mertensiana	55	20	.07	75.97	4	750	0

Table 9—Parameter values for shade tolerance equation

Species	IREG[1]				DBHMX[2]	B1[3]	HMAX[2]	B4[3]	GRANGE
	1	2	3	4					
Abies amabilis	1	1	1	1	183	15612	6096	0.9	1.25
Abies grandis	1	1	0	0	183	12493	7096	1.0	1.31
Abies lasiocarpa	1	1	1	1	61	7404	3040	1.0	1.25
Abies procera	1	1	1	0	220	54435	7920	.9	0.82
Acer macrophyllum	1	1	1	1	50	19044	1524	1.2	.37
Alnus rubra	1	1	1	1	75	130	1320	2.0	.24
Arbutus menziesii	1	1	0	1	120	5047	2438	1.1	1.38
Castanopsis chrysophylla	1	0	0	0	90	15192	3500	1.1	1.38
Chamaecyparis nootkatensis	1	1	1	1	150	3135	5334	1.1	1.73
Libocedrus decurrens	1	0	0	0	120	2243	4500	1.0	1.73
Picea engelmannii	1	1	1	0	102	3313	4877	.9	1.31
Picea sitchensis	0	0	1	1	230	12391	7500	1.0	1.31
Pinus contorta	1	1	1	1	75	6650	3048	1.0	.78
Pinus lambertiana	1	0	0	0	125	12233	5500	.9	1.13
Pinus monticola	1	1	1	1	205	15645	6096	.9	1.04
Pinus ponderosa	1	0	0	0	125	14377	6000	.9	1.14
Pseudotsuga menziesii	1	1	1	1	220	13193	9000	1.1	1.00
Quercus garryana	1	1	0	0	90	4956	2500	1.1	.74
Thuja plicata	1	1	1	1	300	3186	6300	1.0	1.73
Tsuga heterophylla	1	1	1	1	122	17645	6858	.9	1.47
Tsuga mertensiana	1	1	1	1	102	9048	4572	1.0	1.11

[1]Values from Fowles (1979).

[2]Values from Franklin and Dyrness (1973), Fowles (1965), and Pardo (1973).

[3]Adjusted form values given in Reed and Clark (1979) so that a given ton is equivalent to [illegible].

Subroutine BIRTH

The subroutine BIRTH is based on the FORET model of Shugart and West (1977) (figure 3 presents a flow chart for the routine). Species available for regeneration are selected depending on the existing water stress, temperature range, and geographic region of the plot.

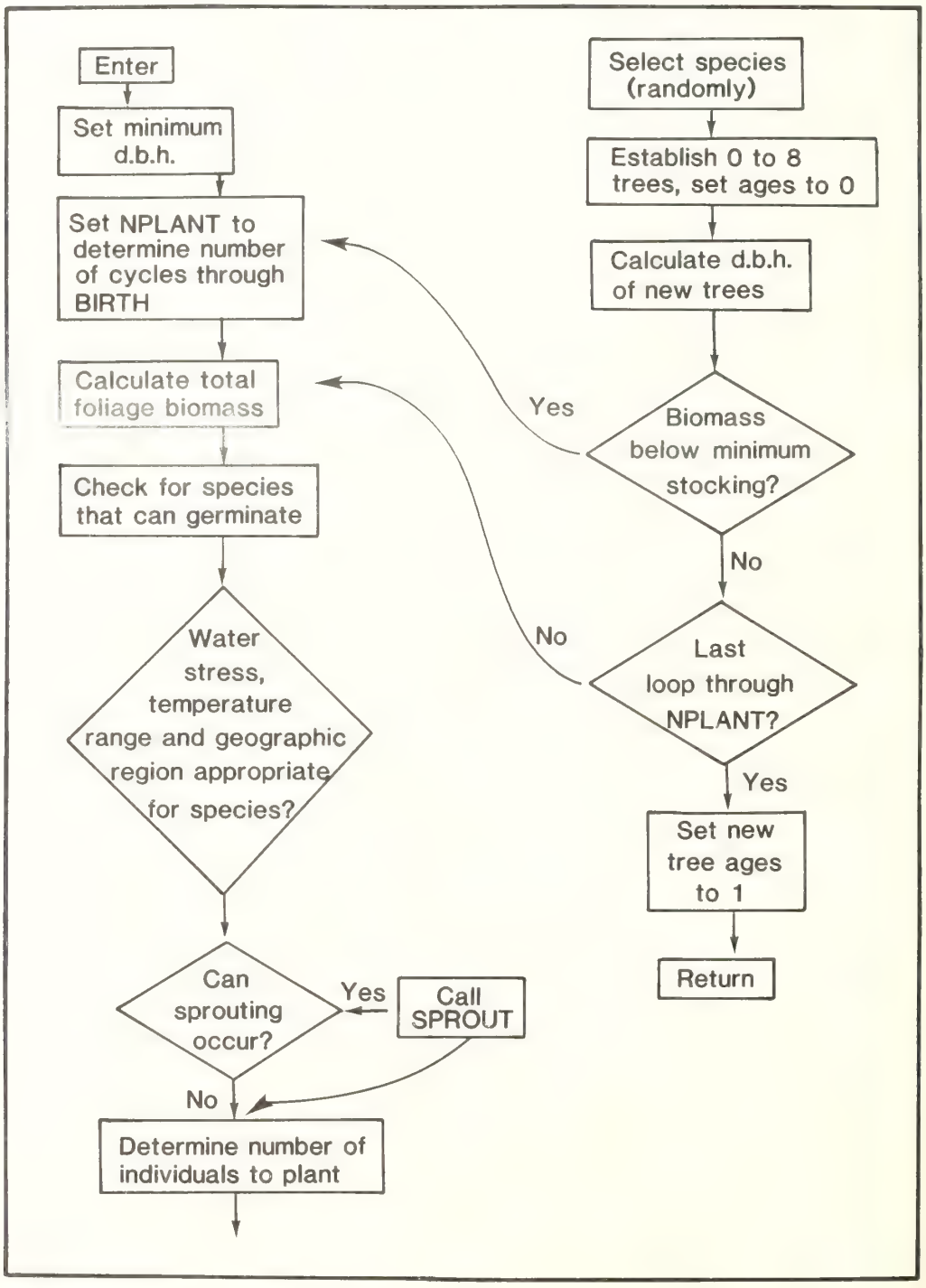

Figure 3.—Flow chart for subroutine BIRTH.

Regeneration depends on the projected leaf area of any existing trees. During the first year any available species can regenerate. Thereafter if the projected leaf area is greater than 3 m^2/m^2 (square meter of leaf area per square meter of ground), *Pinus contorta* Dougl. ex Loud., *P. ponderosa* Dougl. ex Laws., and *Quercus garryana* Dougl. ex Hook. cannot regenerate. If the projected leaf area is greater than 6 m^2/m^2, then *Abies procera* Rehd., *Alnus rubra* Bong., *Arbutus menziesii* Pursh, *Castanopsis chrysophylla* (Dougl.) A. DC., *Picea engelmannii* Parry ex Engelm., and *Pseudotsuga menziesii* cannot appear in the plot. For a projected leaf area exceeding 8 m^2/m^2 *Abies grandis* (Dougl. ex D. Don) Lindl.), *A. lasiocarpa* (Hook.) Nutt., *Acer macrophyllum* Pursh, *Picea sitchensis* (Bong.) Carr., *Pinus lambertiana* Dougl., and *P. monticola* Dougl. ex D. Don cannot appear. If the projected leaf area exceeds 10 m^2/m^2, *Libocedrus decurrens Torr.*, *Chamaecyparis nootkatensis* (D. Don) Spach, *Thuja plicata* Donn ex D. Don, and *Tsuga mertensiana* (Bong.) Carr. cannot regenerate. At leaf areas exceeding 10 m^2/m^2 only the most shade tolerant species, *Abies amabilis* Dougl. ex Forbes and *Tsuga heterophylla* (Raf.) Sarg., can regenerate. The trees appear in the plot when they are between 10 and 15 cm d.b.h. This limit on size is necessary because numbers of smaller seedlings become so large that computer time is prohibitive, and the abundance of very small seedlings may not reflect the composition of an understory that could replace large-canopy trees.

The projected leaf area (XLAI) (in m^2/m^2) is based on foliage biomass (FB10) of all trees on the plot. The equations for the foliage biomass of trees less than 50 cm (19.7 in) in diameter are from Binkely (1983) for *Alnus rubra* and from Gholz and others (1979) for all other species. Because the data range of Gholz' equations is exceeded for large trees (DBH > 50) (fig. 4), the equations for the foliage bio-

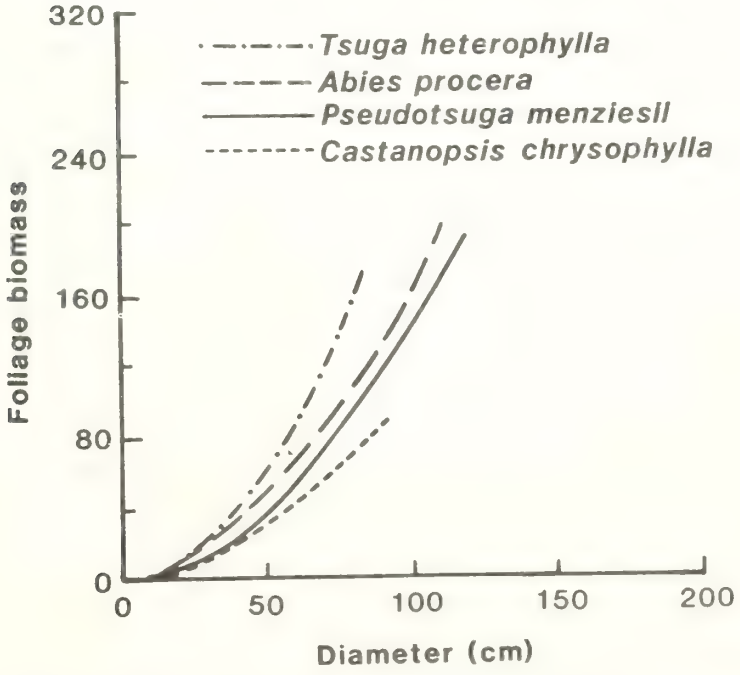

Figure 4.—Foliage biomass as related to diameter using the equations of Gholz and others (1979). A warning is given by Gholz and others (1979) that "maximum and minimum values from the data set...do not necessarily mean that the equation provides reasonable numbers at these extremes." Because of problems in exceeding the data ranges, the foliage biomass-d.b.h. relationship was modified using figure 5, as described in the text.

mass of large trees are calculated indirectly. The sapwood-diameter equation for *Pseudotsuga menziesii* has been obtained by regression analysis.[1] Foliage biomass can then be calculated from the foliage biomass-sapwood area ratio (Grier and Waring 1974) (fig. 5). To estimate the foliage biomass for large trees of other species, a multiplier is calculated from the ratio of the foliage biomass at 50 cm diameter of the species being considered to that of *P. menziesii* at 50 cm diameter. The multiplier is used to adjust the foliage biomass equations from Gholz and others (1979) for trees larger than 50 cm.

[1] Personal communication, R. H. Waring, School of Forestry, Oregon State University, Corvallis, Oregon.

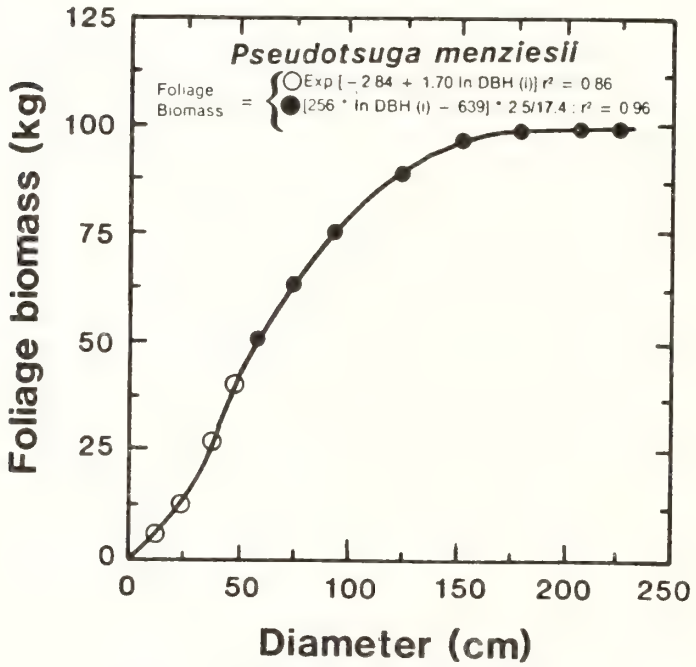

Figure 5.—Foliage biomass as related to diameter for *Pseudotsuga menziesii*.

The equations are as follows:

$$FBIO = \begin{cases} \exp[A_2(i) + BC(i) \ln DBH(k)] & DBH(k) \leq 50,\ i \neq 6 \\ 3.2 + 1.89 \ln (DBH(k)), & DBH(k) \leq 50,\ i = 6 \\ [256 * \ln (DBH(k)) - 639] * 2.5 * DRANGE(i)/C(16), & DBH(k) > 50 \ ; \end{cases}$$

where:

$i = 1,...,NSPEC$ (NSPEC = total number of species)
($i = 6$ = *Alnus rubra*),

$i = 1,...,NTOT$ (NTOT = total number of trees),

$A_2(i)$, $BC(i)$ = parameters from Gholz and others (1979) (see table 7),

$DBH(k)$ = diameter at breast height of tree k (cm),

$DRANGE(i)$ = the ratio of the foliage biomass of species i to that of *P. menziesii* at 50 cm, and

$C(16)$ = conversion from kg to m^2 for *P. menziesii*.

To calculate the leaf area for each tree the foliage biomass is multiplied by the factor $C(i)$ to convert from kg to m^2 and is divided by 2.0 for deciduous trees and 2.5 for conifers to convert total leaf area to projected leaf area.[2] The projected leaf areas are then summed for all trees and divided by the plot size (2000 m^2) to obtain a value for square meter of leaf area per square meter of ground surface:

$$XLAI = \sum_{k=1}^{NTOT} \frac{C(i)\ FBIO/P(i)}{2000} \ ;$$

where: $P(i) = \begin{cases} 2.0 \text{ if } i \text{ is a deciduous tree and} \\ 2.5 \text{ if } i \text{ is a coniferous tree} \ . \end{cases}$

The projected leaf area of the plot is tested against the maximum leaf area at which available species can regenerate. If the projected leaf area is less than the species maximum, a random number of saplings (from 1 to 8) enters the plot. Each introduced sapling has a randomly selected diameter of 10 to 15 cm (3.9 to 5.9 in).

Sprouting may occur depending on tree size (subroutine SPROUT). Species that reproduce vegetatively in this manner are *Acer macrophyllum, Alnus rubra, Castanopsis chrysophylla, Quercus garryana,* and *Arbutus menziesii.*

BIRTH continues until the projected leaf area exceeds 1.0 m^2/m^2 resulting in full stocking the first year of the model run.

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[2] Leaf area conversions from personal communication, R. H. Waring, School of Forestry, Oregon State University, Corvallis, Oregon, based on Grier and Waring (1974).

Subroutine GROW

Subroutine GROW calculates diameter increment for each tree (fig. 6). The annual diameter increment function is similar to that used by Botkin and others (1972), Shugart and West (1977), and Mielke and others (1978). CLIMACS is unique in that it incorporates a specific function for the effect of soil moisture upon growth. Diameter growth takes into account the following conditions:

1. Growth per year is dependent upon existing foliage biomass
2. Growth decreases as tree size increases
3. Temperature affects photosynthetic rate
4. Available moisture affects growth
5. Competition influences growth
6. Shading and shade tolerance affect growth.

Optimum Growth Per Year

The growth subroutine calculates the maximum growth of a species and modifies that optimal growth by size and site considerations. There is strong evidence that diameter growth is related to existing foliage biomass (Grier and Logan 1977). CLIMACS uses a nonlinear relationship between leaf biomass and growth: to calculate optimal diameter increment $B_1(i)\ FBIO^{B}4^{(i)}$. The parameters for this relationship are adjusted from those of Reed and Clark (1979) to give reasonable diameter increments for trees 50 cm (19.7 in) in diameter.

Decreases in Growth Rate Related to Size

As a tree increases in size, an increasing portion of its photosynthetic output is used in respiration and not in producing additional tissue. The phenomenon of decreasing growth in large trees is represented by the following calculation from Botkin and others (1972):[3]

$$1 - \frac{DBH(j)}{DBHMX(i)} \quad \frac{HT(j)}{HMAX(i)} ;$$

for species i and tree j.

As a tree becomes very large, growth approaches zero. Maximum diameter and height were chosen for each species to represent large but not the largest trees of a species to avoid record-sized stands.

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[3] Symbols are defined in table 5 and parameter values given in table 7. Because growth is conditioned by the maximum diameter and height for the species, the maximum values determine the upper limit for tree growth. When using the data for record trees (Fowles 1965, Pardo 1973) the model always grows Site 1 trees. The current values for DBHMX(i) and HMAX(i) are for large but not the largest trees of a species (from Franklin and Dyrness 1973).

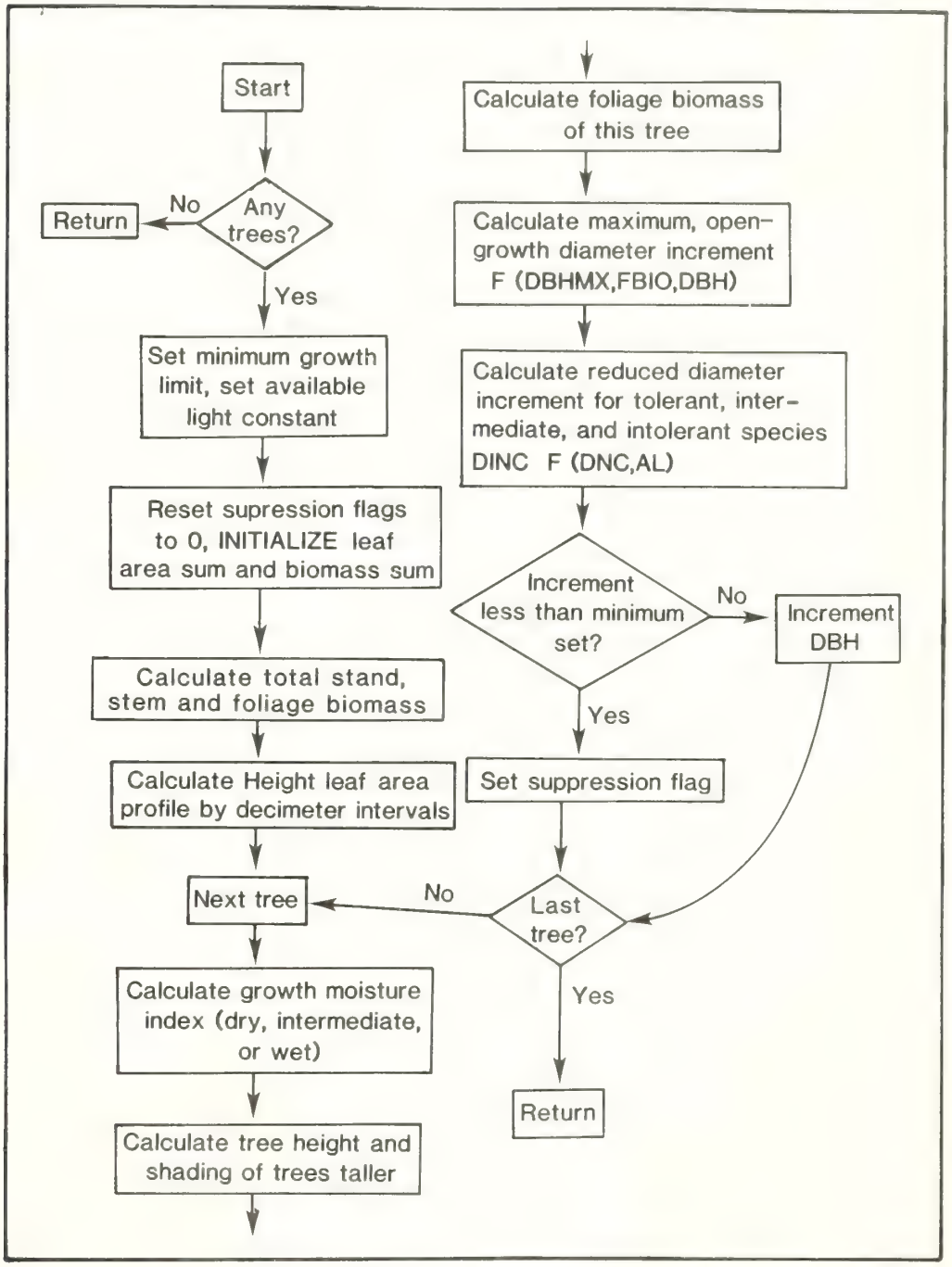
Start
Any trees?
No
Return
Yes
Set minimum growth limit, set available light constant
Reset supression flags to 0, INITIALIZE leaf area sum and biomass sum
Calculate total stand, stem and foliage biomass
Calculate Height leaf area profile by decimeter intervals
Next tree
Calculate growth moisture index (dry, intermediate, or wet)
Calculate tree height and shading of trees taller
Calculate foliage biomass of this tree
Calculate maximum, open-growth diameter increment F (DBHMX,FBIO,DBH)
Calculate reduced diameter increment for tolerant, intermediate, and intolerant species DINC F (DNC,AL)
Increment less than minimum set?
No
Increment DBH
Yes
Set suppression flag
Last tree?
No
Yes
Return

Figure 6.—Flow chart for subroutine GROW

Table 10—Regression values for height as compared to diameter where $HT = 137 + B_2\ DBH + B_3\ DBH^2$ *

Species	Stressed or nonstressed[1/]	B_2	B_3	R^2	N	D.b.h. range
						Centimeters
Pseudotsuga menziesii	Stressed	72.34	-0.22	0.98	55	9.8 - 196.4
	Nonstressed	80.44	-.23	.96	65	22.3 - 200.4
Tsuga heterophylla	Stressed	75.97	-.27	.98	38	4.9 - 143.4
	Nonstressed	81.21	-.27	.97	39	6.8 - 130.0
Abies procera	Stressed	68.29	-.19	.98	24	48.1 - 127.3
Abies amabilis	Nonstressed	85.60	-.55	.98	19	16.7 - 62.0
Tsuga mertensiana	Nonstressed	55.29	-.07	.98	23	32.2 - 84.2
Thuja plicata	Nonstressed	64.71	-.23	.98	38	6.2 - 157.9

*Data is from research stands in the H. J. Andrews Experimental Forest.

1/Stressed trees are growing in a habitat where PMS < 15 or TGI > 60.

The height-diameter relationship used for some species is based on that used by Botkin and others (1972) and Mielke and others (1978). The parabolic equation follows from a discussion in Ker and Smith (1955). Height (HT) is a function of the diameter at breast height (DBH):

$$HT(j) = 137 + B_2(i)\ DBH(j) - B_3(i)\ DBH(j)^2.$$

The constants $B_2(i)$ and $B_3(i)$ are chosen so that height is at a maximum and the rate of change of height with respect to diameter is zero ($dHT(j)/dDBH(j) = 0$) when $DBH(j)$ is at a maximum:

$$B_2(i) = \frac{2(HMAX(i) - 137)}{DBHMX(i)}, \text{ and}$$

$$B_3(i) = \frac{HMAX(i) - 137}{DBHMX(i)^2}.$$

The rate of change in height decreases as the diameter increases. For *Tsuga heterophylla, T. mertensiana, Thuja plicata, Pseudotsuga menziesii, Abies amabilis,* and *A. procera* height was estimated directly from diameter using equations developed by regression analyses of diameter-height data from the H.J. Andrews Experimental Forest (Willamette National Forest, Oregon) (table 10). Sufficient data were not available to treat all species in this manner. Because height growth is related to habitat and *Tsuga heterophylla* and *P. menziesii* were sampled in a variety of habitats, regressions for these two species were also performed for temperature- or moisture-stressed stands (TGI > 60 or PMS < 15) and nonstressed stands. In stressed stands the height growth is less—particularly for large trees (fig. 7).

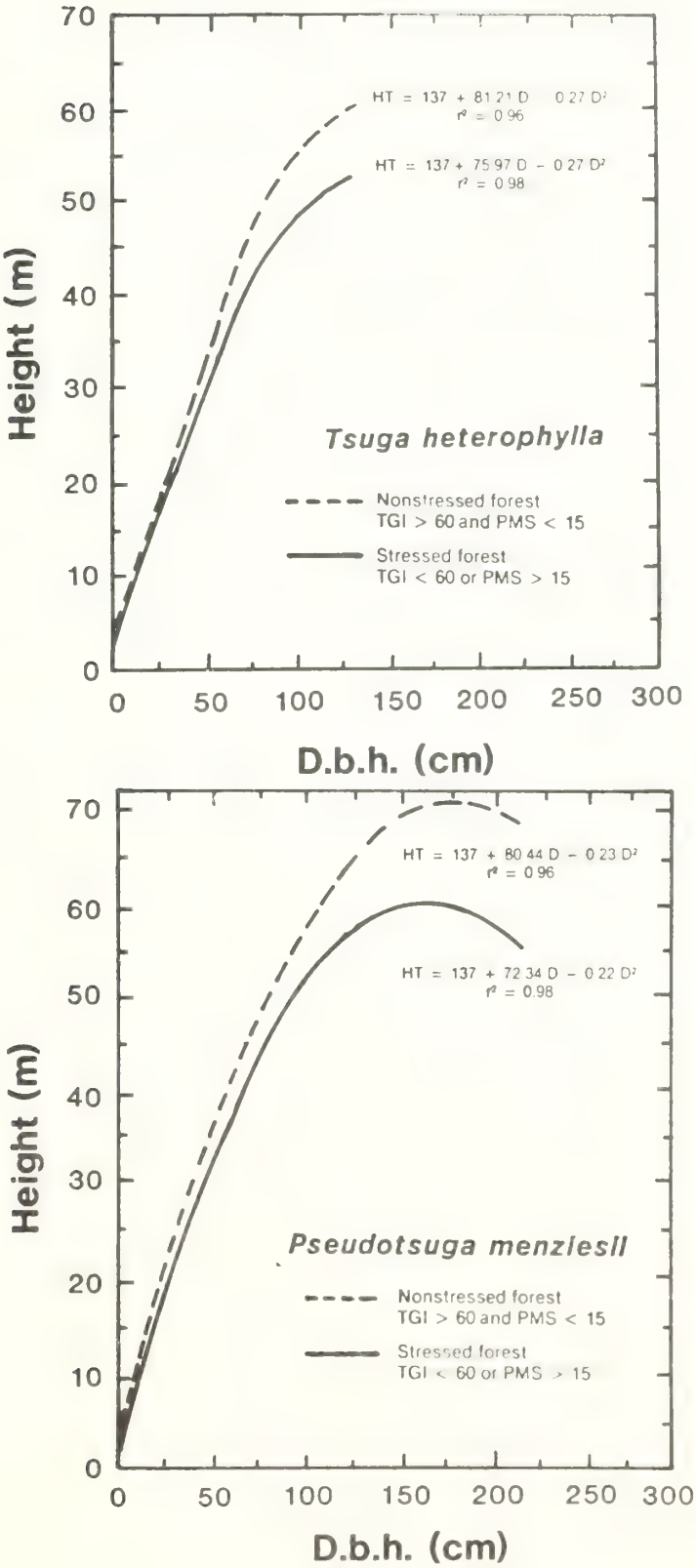
Height (m)
D.b.h. (cm)
HT = 137 + 81.21 D − 0.27 D²
r² = 0.96
HT = 137 + 75.97 D − 0.27 D²
r² = 0.98
Tsuga heterophylla
Nonstressed forest
TGI > 60 and PMS < 15
Stressed forest
TGI < 60 or PMS > 15
HT = 137 + 80.44 D − 0.23 D²
r² = 0.96
HT = 137 + 72.34 D − 0.22 D²
r² = 0.98
Pseudotsuga menziesii
Nonstressed forest
TGI > 60 and PMS < 15
Stressed forest
TGI < 60 or PMS > 15

Figure 7.—Tree height as related to diameter for *Tsuga heterophylla* and *Pseudotsuga menziesii* for stressed and nonstressed stands from regression analysis.

Temperature

The effect of temperature on the photosynthetic rate is modeled with a parabolic equation that ranges from 0 to 1 (following Botkin and others 1972):

$$TEGD = \frac{4(TGI - DMIN(i))\ (DMAX(i) - TGI)}{(DMAX(i) - DMIN(i))^2}$$

A value of 0 occurs for TGI less than the minimum degree days (DMIN(i)) or greater than the maximum degree days (DMAX(i)). Thus, this function reflects the temperature range in which a species can grow. The values for DMIN(i) and DMAX(i) are from Emmingham and Waring.[4]

Effects of Moisture

The inclusion of the moisture index (WATDEX) in the equation for diameter increment is necessary due to the major influence of available moisture on the growth of tree species in the Pacific Northwest (Franklin and Waring 1980). In this model the effect of available moisture on growth is represented by a beta function (following Reed and Clark 1979):

$$WATDEX = \beta(a,b,c,x) = \begin{cases} \dfrac{(x-a)\ (c-x)^v}{(b-a)\ (c-b)}, & \text{for } x \varepsilon (a,c) \\ 0, & \text{otherwise ;} \end{cases}$$

where: x = PMS,
c = WMIN(i) = the minimum value of water stress for a species (−bars),
a = the negative x-intercept,
b = the optimum PMS for growth (−bars), and
v = $(c-b)/(b-a)$.

See table 11 for a list of the parameter values.

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[4] Personal communication, W. Emmingham and R. H. Waring, School of Forestry, Oregon State University, Corvallis, Oregon

Table 11—Parameter values for moisture index[1]

Moisture	a	b	Species
Dry	-10	5	Abies grandis, Arbutus menziesii, Acer macrophyllum, Castanopsis chrysophylla, Libocedrus decurrens, Pinus contorta, P. lambertiana, P. ponderosa, Pseudotsuga menziesii, Quercus garryana
Intermediate	-8	1	Abies amabilis, A. lasiocarpa, A. procera, Picea engelmannii, Pinus monticola, Thuja plicata, Tsuga heterophylla, T. mertensiana
Moist	-2	0	Alnus rubra, Chamaecyparis nootkatensis, Picea sitchensis

[1]The parameters, a and b, are explained in the text.

According to the model, dry site species have a high value of WATDEX for most values of PMS (see fig. 8). Intermediate site species, such as *Tsuga heterophylla*, grow only at lower PMS values, and the wet site species, such as *Picea sitchensis*, have a positive value of WATDEX only at very low values of PMS.

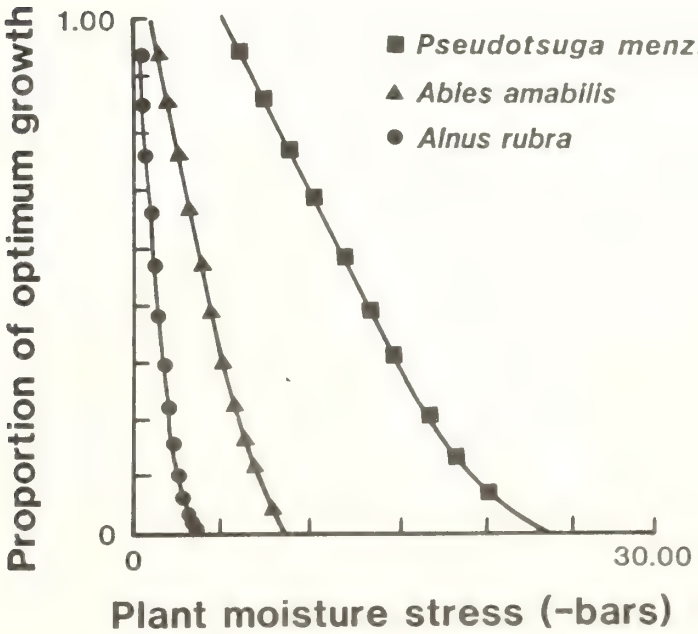

Figure 8.—The effect of plant moisture stress upon diameter increment.

Competition for Nutrients

The crude expression for rooting space competition, which reflects competition for nutrients, is from JABOWA (Botkin and others 1972) and is dependent upon the total aboveground biomass (TBIO) and the maximum biomass a stand can support (SOILQ): 1 − TBIO/SOILQ. The total aboveground biomass (TBIO) is the sum of the foliage biomass and stemwood biomass. The equations for stemwood biomass are from Gholz and others (1979):

$$SBIO = \begin{cases} 0.02 + 2.09\ DBH(j) - .0015\ DBH(j)^2, & i = 6\ (\textit{Alnus rubra}) \\ \exp(A_1(i) + BB(i)\ \ln\ DBH(j))\ , & i \neq 6\ ; \end{cases}$$

where $A_1(i)$ and $BB(i)$ are parameter values from Gholz and others (1972) (table 7). The data range for the Gholz equations for stemwood biomass does not include large trees. To assess the impact of this problem stemwood biomass was plotted against values from yield tables (MacLean and Berger 1976) (fig. 9). Modeled and measured biomass values for *Calocedrus decurrens* and *Pinus ponderosa* compare well, but the predicted curve for *Pseudotsuga menziesii* stemwood biomass is greater than measured biomass at large diameters. As there are no data available, evaluation of this discrepancy is not possible.

The maximum biomass for a site (SOILQ) is obtained from recorded values of natural stands similar to the habitat for which the model is being run. As TBIO approaches SOILQ from below, (1-TBIO/SOILQ) approaches 0, and diameter increment decreases. When TBIO exceeds SOILQ, (1-TBIO/SOILQ) becomes negative; no diameter increase occurs. The value for SOILQ should be chosen carefully because evaluation of the model output suggests that the stand biomass is strongly influenced by this value.

Shade Tolerance

Diameter growth is also related to the light a tree receives and its shade tolerance. The regulation of photosynthetic rate by available light is expressed as:

$$1 - \exp(-t_1(AL - t_2))\ ;$$

where t_1 and t_2 are species specific parameters (see table 12). The available light a tree receives (AL) is based on the total foliage area of all trees in the plot that are taller than the tree being considered (fig. 10 illustrates how available light changes over time). The canopy is broken into tree height intervals by decimeters. The sum of the leaf areas of all trees in height classes greater than the one being considered is calculated and stored as the shading leaf area (SLAR). Available light is then found by using an equation modified from Botkin and others (1972) and Mielke and others (1978):

$$AL = PHI * \exp(-0.26\ SLAR)\ ;$$

where PHI = 1.0 is the annual insolation (in appropriate units).

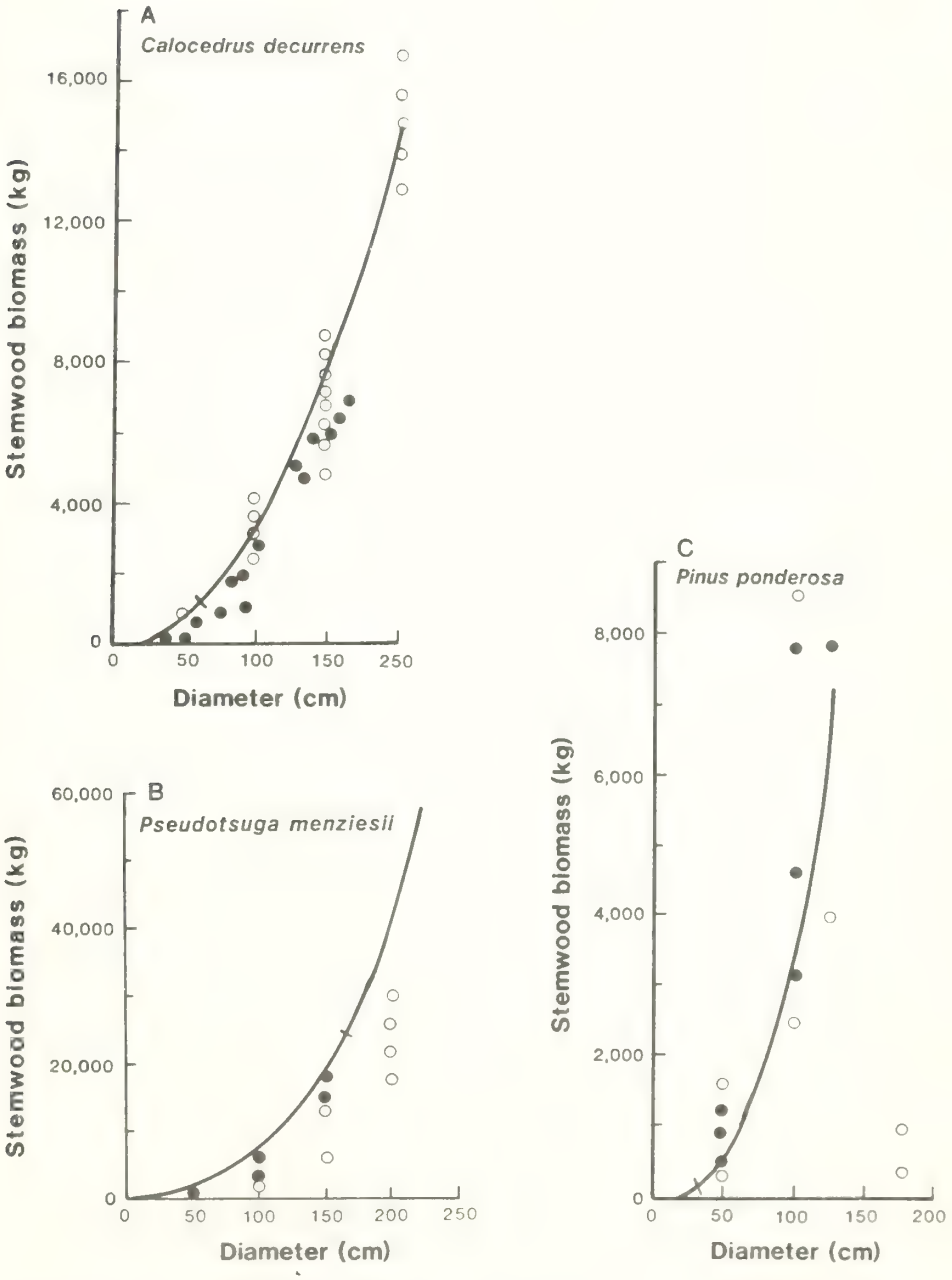

Figure 9.—The relationship of stemwood biomass to diameter for (**A**) *Calocedrus decurrens*, (**B**) *Pseudotsuga menziesii*, and (**C**) *Pinus ponderosa*. The curves are from Gholz and others (1979), and the line crossing the curve indicates the end of the data range. Circles are from volume tables in MacLean and Berger (1976) with solid circles being inside and open circles outside the range of sampled trees

Table 12—Parameter values for shade tolerance equation

t_1	t_2	Shade tolerance class based on Minore (1979)
23.026	0.30	Quercus garryana, Pinus ponderosa, P. contorta
9.695	.025	Acer macrophyllum, Alnus rubra, Castanopsis chrysophylla, Arbutus menziesii, Picea engelmanni, Abies procera
20.467	.025	Abies grandis, A. lasiocarpa, Pinus lambertiana, P. monticola P. sitchensis, Pseudotsuga menziesii,
32.846	.025	Libocedrus decurrens, Chamaecyparis nootkatensis, Thuja plicata, T. mertensiana
40.0	.025	Abies amabilis, Tsuga heterophylla

[1]The relative diameter growth is equal to (1-exp (-t_1 (AL-t_2))) for AL being the available light derived from the projected leaf area (m^2/m^2).

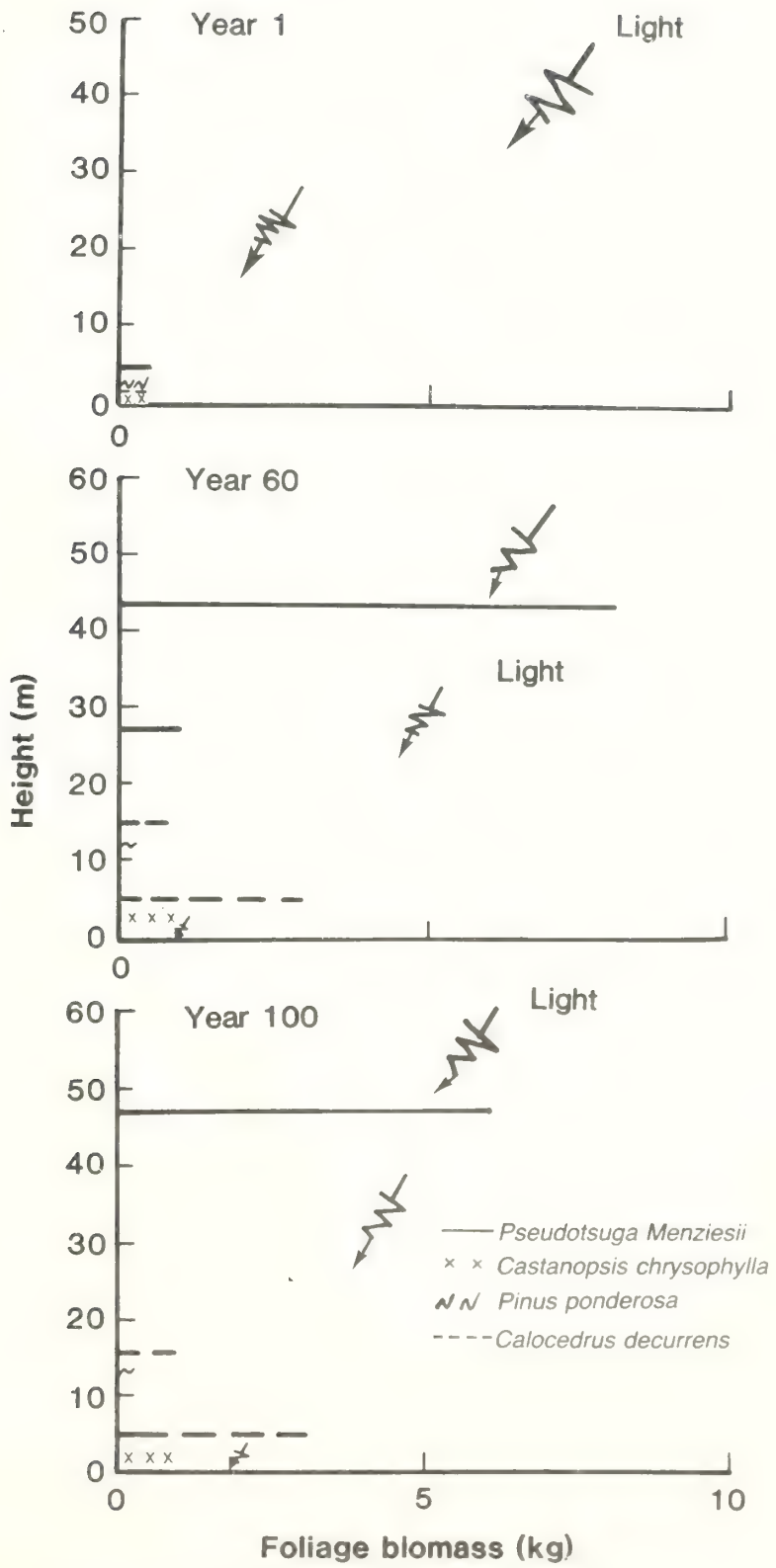

Figure 10.—The relationship of height to foliage biomass from a simulation model. The size of the arrow representing light is meant to depict the amount of light reaching the canopy at each level.

CLIMACS includes five curves that translate available light into photosynthetic capacity based on shade tolerance (fig. 11). *Pinus ponderosa* is the least tolerant of the Pacific Northwest species and cannot grow under a leaf area greater than 5 m^2/m^2 (Minore 1979; Waring).[5/] Hardwoods, intolerant conifers, and tolerant conifers, respectively, represent increasing levels of shade tolerance (Minore 1979). In the model the greatest difference in these categories occurs at a projected leaf area of 8 m^2/m^2.

Diameter Increment Equation

The diameter increment equation is a multiplicative function of six factors:

$$DINC = \left(\frac{1 - DBH(j)\ HT(j)}{DBHMX(i)\ HMAX(i)}\right)\left(\frac{DBH(j)\ B_1(i)\ FBIO^{B}4^{(i)}\ (1-TBIO/SOILQ)TEGD}{274 + 3B_2(i)\ DBH(j)^2 - 4B_3(i)\ DBH(j)^3}\right)$$

$$\times\ (WATDEX) \times [1 - \exp(-a_1(AL-a_2))]\ ;$$

where: $j = 1,...,NTOT$ = the tree number and
$i = 1,...,NSPEC$ = the tree species code.

This assumes that optimum growth is modified by the effects of temperature, moisture availability, competition, and shade tolerance, all acting independently. A multiplicative function is the most common relationship used (Botkin and others 1972, Reed and Clark 1979, Shugart and West 1977) but can tend to underestimate growth if many factors are incorporated (Swartzman and Bentley 1979).

[5/] Personal communication, R. H. Waring, School of Forestry, Oregon State University, Corvallis, Oregon.

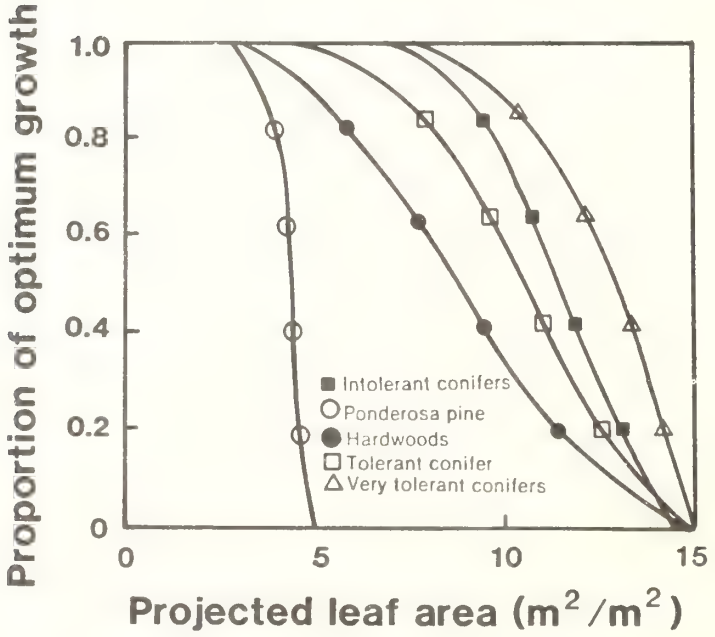

Figure 11.—The effect of shade tolerance on diameter growth

Subroutine KILL

Much of the existing literature on mortality predicts death of a tree based on its crown quality or vigor class (Graham 1980, Hamilton and Edwards 1976, Staebler 1953). Because we cannot identify crown features in the current model structure, individual tree mortality is based on diameter, the maximum diameter for the species, and the life history of the species (see fig. 12). A tree is subjected to KILL if

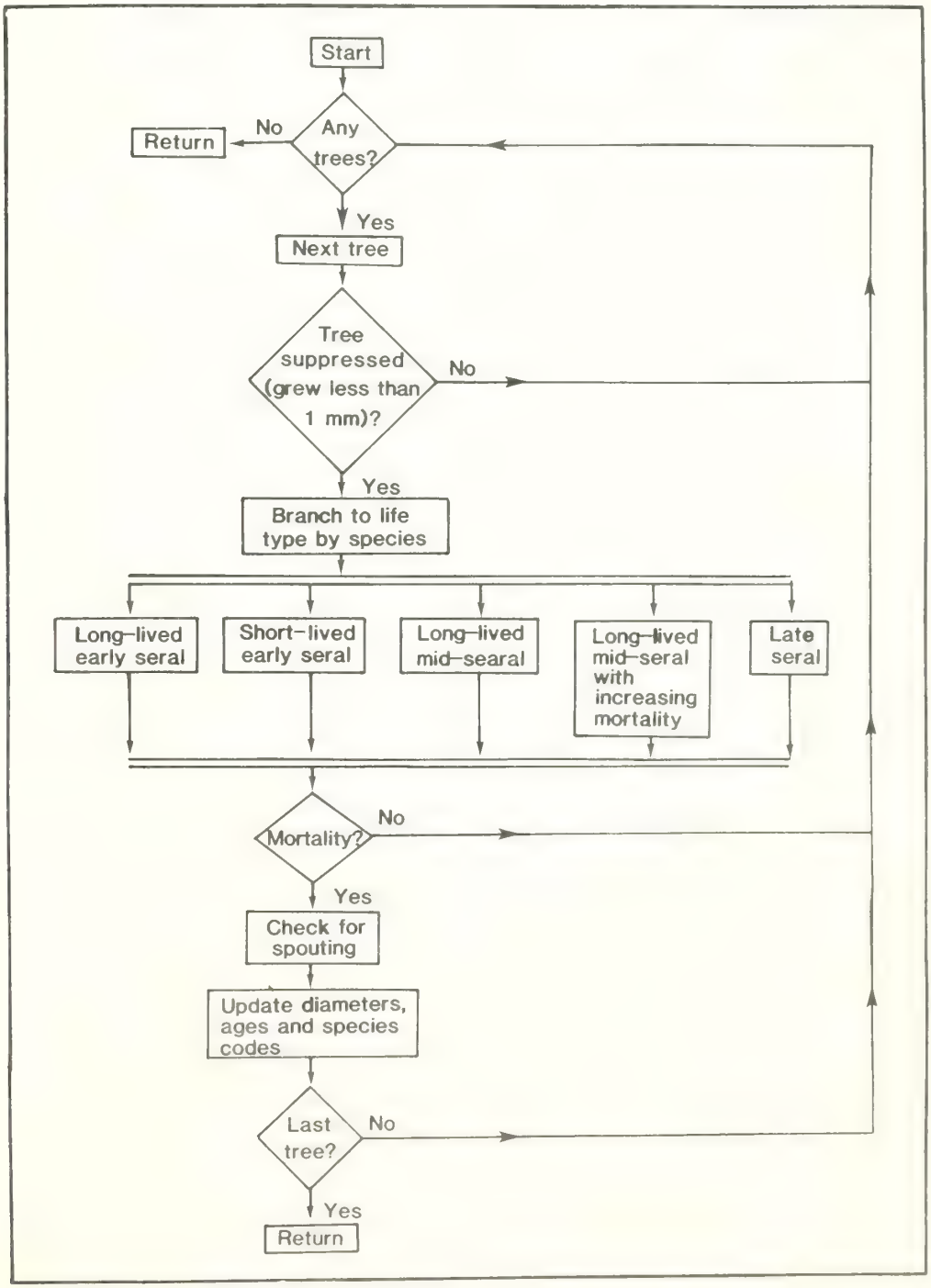

Figure 12.—Flow chart for subroutine KILL.

Table 13—Equations for slow growth-related mortality

Successional status	Conditions	Probability of surviving 1 year	Species
Long-lived early seral	DBH < 0.2DBHMX	$0.8866 + \frac{0.1029}{0.2-1/DBHMX}\left(\frac{DBH-1}{DBHMX}\right)$	*Pinus ponderosa* *Pseudotsuga menziesii*
	DBH ≥ 0.2DBHMX	0.9895	
Short-lived early seral		0.628	*Acer macrophyllum* *Alnus rubra* *Arbutus menziesii* *Quercus garryana*
Long-lived mid-seral	DBH < 0.1 DBHMX	$0.96496 + \frac{0.01294}{.1-1/DBHMX}\left(\frac{DBH-1}{DBHMX}\right)$	*Chamaecyparis nootkatensis* *Libocedrus decurrens* *Thuja plicata*
	DBH ≥ 0.1 DBHMX	$0.97556 + \frac{0.02339\ DBH}{DBHMX}$	
Long-lived mid-seral with increasing mortality	DBH < 0.5DBHMX	$0.8866 + \frac{0.1112}{0.5-1/DBHMX}\left(\frac{DBH-1}{DBHMX}\right)$	*Abies grandis* *A. lasiocarpa* *A. procera* *Picea engelmannii* *P. sitchensis* *Pinus contorta* *P. lambertiana* *P. monticola*
	DBH ≥ 0.5DBHMX	$1.0538 - \frac{0.1112\ DBH}{DBHMX}$	
Late seral	DBH < 0.1 DBHMX	$0.9956 + \frac{0.99335}{0.1-1/DBHMX}\left(\frac{DBH-1}{DBHMX}\right)$	*Abies amabilis* *Tsuga heterophylla* *T. mertensiana*
	DBH ≥ 0.1 DBHMX	$1.0053 - \frac{0.0635\ DBH}{DBHMX}$	

Compiled from McArdle and others (1949) and from unpublished data from a chronosequence of stands in the Cascade Range in Oregon and Washington (Ted Thomas, USFS, Forestry Sciences Laboratory, Corvallis).

diameter growth is less than 1 mm (0.04 in) in any year. We classified tree species into five groups based on mortality pattern using data from a chronosequence of stands in the Cascade Range (table 13). Short-lived, early seral species have a constant survival probability of 0.628 for 1 year. For all other successional classes, mortality changes with the tree size (fig. 13). Long-lived, early seral species have increasing survival until 20 percent of the maximum diameter is reached, at which point the probability of dying becomes constant. Late seral species have an increasing probability of survival until 10 percent of the maximum diameter is attained; then the probability of surviving tapers off slowly. For long-lived, mid-seral species the probability of survival slowly increases as size increases. Long-lived, mid-seral species with increasing mortality have a peak of surviving at 50 percent of the maximum diameter; the probability of death increases on either side of this asymptote.

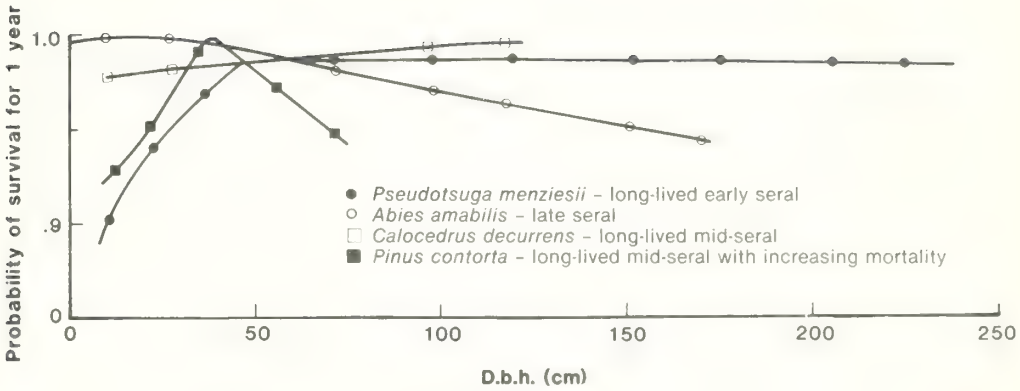

Figure 13.—Probability of tree survival 1 year after slow growth (less than 1 mm [0.04 in] of diameter increment) for four successional classes. A fifth class, short-lived early-seral species, has a constant survival probability of 0.628.

Subroutine DISTRB

The subroutine DISTRB models natural and human disturbances to the ecosystem. Fires are the most common natural disturbances to forests of the Pacific Northwest (Hemstrom 1979), and windthrows can cause localized disturbances Clearcuttings are simulated on user-specified rotation bases with *Pseudotsuga menziesii* planted after the cut (other species could be planted). Each of these disturbances can be introduced at user-specified intervals and intensities (see subroutine INPUT, Appendix 1).

Because the BIRTH subroutine results in small trees (that is, the seedling stage is skipped), model year 1 is approximately stand year 30 (assuming a 10- to 15-cm (3.9- to 5.9-in) tree is found on a 30-year-old-stand). A disturbance should be thought of as occurring approximately 30 years in the past. Thus a disturbance interval of 100 years results in the disturbance occurring in model years 100, 200, 300, etc., or in stand years 130, 260, 390, etc.

Following an episodic disturbance, the species, the diameter, and the age of all trees killed can be printed out in tabular form and can be saved on a tape for further use (refer to Appendix 1, subroutine INPUT).

Fire

Fire is modeled as an event that causes a high proportion of death for young trees dependent upon the species' tolerance to fire (fig. 14). *Pseudotsuga menziesii, Pinus ponderosa, P. lambertiana, Picea sitchensis, Abies grandis, A. lasiocarpa, A. procera,* and *Quercus garryana* are the species most resistant to fires (Minore 1979; Franklin[6]); and *Abies amabilis, Tsuga heterophylla,* and *T. mertensiana* usually don't survive fire.[7] The probability of a tree surviving a fire (Pr) is related to the intensity of the fire FI ($0 \leq FI \leq 1$):

$$Pr = \begin{cases} \exp(-0.00255*DBH(j))*FI, & i = 2, 3, 4, 12, 14, 15, 16, 17 \\ \exp(-0.00053*DBH(j))*FI, & i = 5, 6, 7, 8, 9, 10, 11, 13, 18, 21 \\ 0 & i = 1, 19, 20 \ . \end{cases}$$

Fire occurs at user-specified intervals. The present model probably works for severe fires that result in stand replacement but is inappropriate for the more frequent and less intense fires in forests dominated by *Quercus garryana* or *Pinus ponderosa.*

Windthrow

The equations for the probability of death of a tree by a catastrophic wind are based on data from Tar Creek in the Clackamas River drainage (see footnote 6). Individual *Pseudotsuga menziesii, Tsuga heterophylla,* and *Thuja plicata* that died as a result of wind between 1948 and 1958 were recorded. All species have an increasing probability of death from wind as size increases (fig. 15). Although large trees have a large surface area upon which the wind can act, smaller trees are frequently in the path of falling large trees. The equations in the model are dependent on size and are conditioned by species and size:

$$P = \begin{cases} (1.6 - \exp(-0.00255*DBH(i)))*FI, & i = 11, 19, 20 \\ (1.9 - \exp(-0.00053*DBH(i)))*FI, & i = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, \\ & \quad 12, 13, 14, 15, 16, 17, 18, 21 \ . \end{cases}$$

Clearcuttings

A clearcutting is modeled as an event that occurs at user-specified rotation times and removes all of the trees. After all trees are removed from a plot, 198 trees per 0.20-ha (0.08-acre) plot of 10- to 15-cm (3.9- to 5.9-in) d.b.h. *Pseudotsuga menziesii* are introduced to mimic the normal planting prescription of 1,000 trees per hectare.

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[6] Personal communication, J. F. Franklin, Pacific Northwest Forest and Range Experiment Station, USDA Forest Service, Corvallis, Oregon.

[7] Personal communication, J. K. Agee, National Park Service Cooperative Park Studies unit, College of Forest Resources, University of Washington, Seattle, Washington.

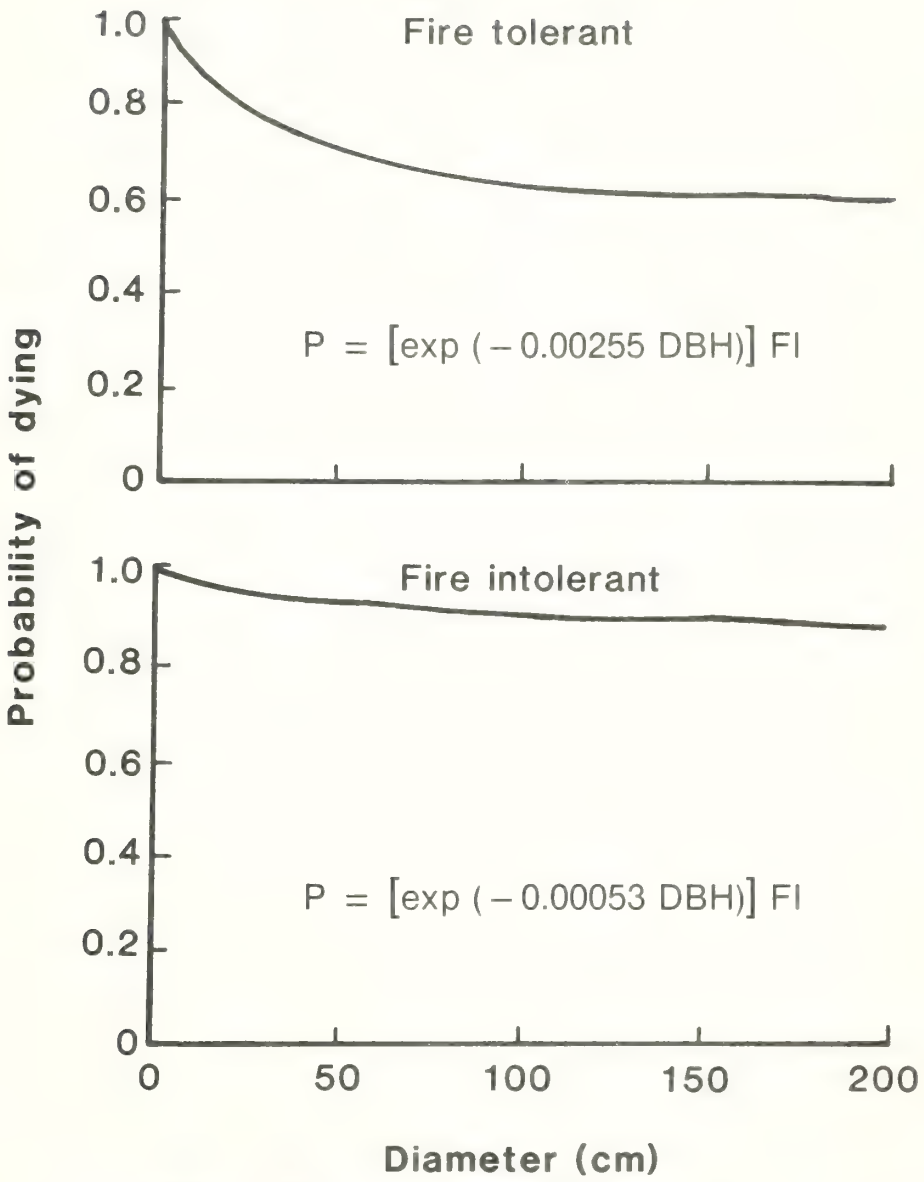

Figure 14.—Probability of death of a tree following a fire for fire-tolerant and fire-intolerant species. *Abies amabilis*, *Tsuga heterophylla*, and *T. mertensiana* do not survive fires in the model. The intensity of the fire can be adjusted by the parameter FI. The most severe fire is depicted (FI = 1)

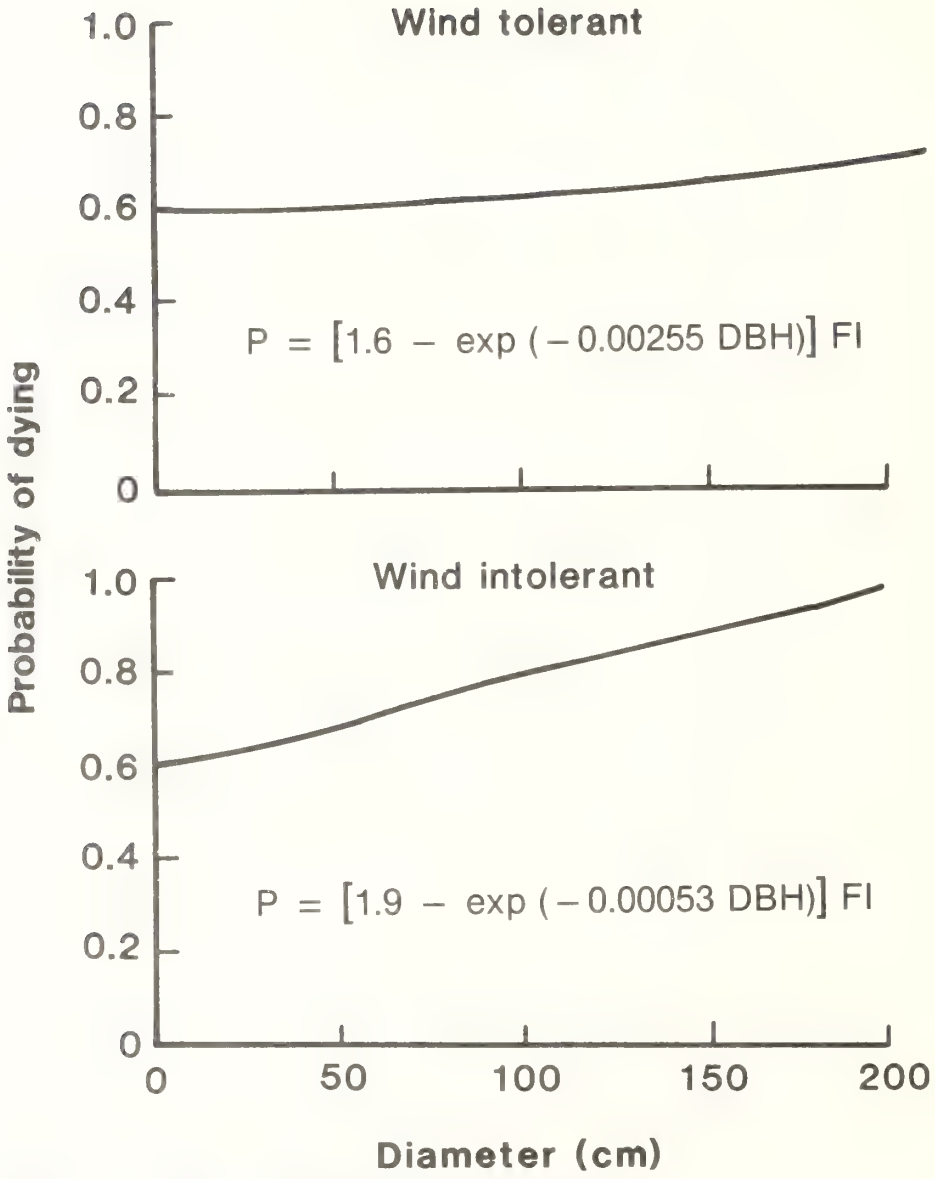

Figure 15.—Probability of death after a windstorm. Species in each tolerance class are listed in the text. The most severe storm is illustrated (FI = 1).

Biological Support of the Model

Biological support of the model is based on three criteria:

1. Scientific rationale of equations and parameter values,
2. Applicability of this model paradigm to at least five forest systems, and
3. Model output compared to data.

CLIMACS has been verified through evaluation of the model equations and parameter values as explained in this text. All relationships and values are based on current knowledge of the tree species of the Pacific Northwest. For large trees, little information exists on the height, stemwood biomass, and foliage biomass relationships to diameter. No studies have documented the change in temperature growth index, plant moisture stress, or leaf area as a stand develops.

The FORTRAN code for CLIMACS is based on models that have been applied to other regions. JABOWA (Botkin and others 1972) simulates forest succession in the northeast United States. Shugart and West (1977) used FORET, the predecessor of CLIMACS, to model the chestnut blight in the Appalachian forest of Tennessee. The FORET model has also been used to project the influence of air pollution on stand development (West and others 1980) and to successfully simulate forest development for a mixed pine-hardwood forest in Arkansas (Mielke and others 1978). Other models derived from the core paradigm have been useful in predicting forest changes in eucalyptus forests of Australia (Shugart and Noble 1981) and in a tropical forest (Doyle and others 1979). Weinstein (1982) examined the diameter increment of a version of FORET and found that the average increment overestimated the diameter changes of trees remeasured after a 13-year interval. This discrepancy was corrected when moisture stress and nutrient limitation were introduced to the model. Both of these factors are in the diameter increment equation in CLIMACS.

Simulations of forests in western Oregon compare well to existing stand structure (Hemstrom and Adams 1982). For xeric and mesic stands nearly 450 years old, CLIMACS projects a stand dominated by *Pseudotsuga menziesii* of a variety of size classes. Projected leaf area, basal area, and foliage biomass of the simulated stand are similar to those of the natural stand (see discussion in Hemstrom and Adams 1982). Differences between the natural and the simulated stand may be due largely to chance and the lack of disturbances in the model forest.

Other comparisons incorporate natural disturbances in the simulation. Projections of 750 years of stand development on the western Olympic Peninsula of Washington State in the aftermath of fire, windstorm, or clearcutting show the major role *Pseudotsuga menziesii* plays (Adams and others 1983). When these disturbances occur at various frequencies, each disturbance results in unique patterns of stand development (Dale and others 1984).

Sensitivity Analysis

A sensitivity analysis is a process to evaluate how sensitive model output is to variation in parameter values. By varying parameters singly and in combination (for those known to be correlated), the influence of the parameter values on model behavior can be assessed. A sensitivity analysis has not been performed on CLIMACS because of a lack of time and money, and we urge that such a study be carried out. In the documentation process, we have noted the sensitivity of the model to the value for the maximum biomass for the forest (SOILQ) and to maximum diameter for each species. The parameters affecting the diameter increment growth, in particular, should be examined carefully. Shugart and West (1979) report that FORET, a forerunner of CLIMACS, is particularly sensitive to plot size. Finn (1979) introduced a form factor to account for crown depth and shading of trees in JABOWA (Botkin and others 1972) and found little effect. Crown form may, nevertheless, affect the development of coniferous forests.

Areas for Improvement

As with any model, CLIMACS can be altered and improved to meet the objectives of the study for which it is being used. Three possible improvements to the model are: (1) altering the mortality curves, (2) changing the vertical structure of each tree, and (3) improving the competition function.

Mortality is a largely unexplored component of successional processes. The model can be used to ask questions about differences in mortality among species by altering the mortality curves (fig. 13) and treating the survival equations as hypotheses to be tested by simulations. A problem with such a simulation study is the lack of data for comparison with model output. Data on survival rates of tagged trees will be available for such a study from permanent plots established by the USDA Forest Service.

The vertical structure of each tree could be modified to more accurately depict the form of a species. This would allow analyses of the role of available habitat for birds and mammals as forests change over time. By correlating breeding habitat to vegetation structure, the probability of a breeding habitat existing under certain management regimes and natural successions could be assessed (for example, Smith and others 1979). These modifications would also allow further study of the impact of leaf area on growth.

The function that models competition for nutrients in the GROW subroutine is a crude approximation. The model applicability would improve by deletion of the parameter SOILQ and incorporation of nitrogen and phosphorus cycling. The problem in including nutrient cycling in the model is depicting an accurate representation but not requiring too many driving variables.

Acknowledgments

This research could not have been completed without the scientific advice, interest, and encouragement and unpublished data provided by Jerry Franklin. We appreciate technical assistance and discussions with Jim Agee, Paul Alaback, Bill Emmingham, Bob Harr, Mark Harmon, Tom Hinckley, Mark Klopsch, Joe Means, Ed Small, Gordie Swartzman, and Dick Waring. The research was supported by contract CX-900-0-E014 from Pacific Northwest Region, the National Park Service, U.S. Department of the Interior. This is Publication Number 2391 of the Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831.

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Appendix 1

Listing of Program CLIMACS

```
(0001)  C      FOREST
(0002)
(0003)  C      ....
(0004)  C      ..   FOREST SUCCESSION MODEL
(0005)  C      .....
(0006)  C
(0007)  C      CONVERSION PROGRAMMERS:   J. HOLT, M. RUST
(0008)  C                                MILNE COMPUTER CENTER, OSU.
(0009)  C
(0010)  CQS
(0011)  CQS     All comments labeled "CQS" were done at the Center for Quantitative
(0012)  CQS     science at the University of Washington using the PRIME.  To run the
(0013)  CQS     model on a CDC note these comments and make the appropriate changes.
(0014)  CQS
(0015)  CQS    PROGRAM CONIFER (INPUT,OUTPUT,TAPE4,TAPE5=INPUT,TAPE6=OUTPUT,TAPE8
(0016)  CQS   1)
(0017)  CQS           (FILE DECLARATIONS BELOW)
(0018)  CQS
(0019)          COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),KSPRT(50),NEWTR(50)
(0020)         1,SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
(0021)  CQS
(0022)  CQS            PRIME STORES  4 CHARACTERS PER REAL ( 1 REAL = 2 WORDS )
(0023)  CQS            CDC   STORES 10 CHARACTERS PER WORD
(0024)  CQS
(0025)  CQS
(0026)          COMMON /PARAM/ AAA(8,100),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
(0027)         1,AGEMX(50),G(50),SPRTND(50),SPRTMN(50),SPRTMX(50),KTIME(50),A1(50)
(0028)         2,A2(50),BB(50),BC(50),C(50),WMIN(50),IREG(50,4),DBHMX(50),B1(50),
(0029)         3B4(50),HMAX(50),DRANGE(50)
(0030)          COMMON /CONST/ NSPEC,SOILQ,PMS,TQI,TQII,SD,IQEOQ
(0031)          COMMON /DEAD/ NOGRO(700)
(0032)          COMMON /COUNT/ NTOT,NYEAR,IPERT,INT,IN,PMORT,FI
(0033)          COMMON /PASSX/ A(501,25),FB(50)
(0034)          COMMON /SEED/ USEED(13)
(0035)          INTEGER USEED
(0036)  CQS
(0037)          DIMENSION Z(2), SPNAM(5,40)
(0038)  CQS
(0039)  CQS       GET SOURCE DEFINITIONS OF K$READ, K$WRIT (TO OPEN FILES)
(0040)  CQS
(0041)
(0042)          NOLIST  /*  SYSCOM>KEYS.F
(0044)          LIST
(0045)
(0046)          DATA  SPNAM              /  200 * '--'  /
(0047)
(0048)          DATA NCT/0/
(0049)
(0050)  CQS     INITIALIZE FILES
(0051)
(0052)          CALL OPEN( 5, 'SUCDAT', 6, K$READ )
(0053)          CALL OPEN( 6, 'OUTPUT', 6, K$WRIT )
(0054)          CALL OPEN( 7, 'TAPE4',  5, K$WRIT )  /* UNIT 4 RESERVED ON PRIME
(0055)          CALL OPEN( 8, 'TAPE8',  5, K$WRIT )
(0056)           CALL OPEN( 9, 'TAPE9', 5, K$WRIT )
(0057)
(0058)
(0059)  C       ..    READ INPUT DATA, PARAMETERS, AND VARIABLES FROM TAPE5.
(0060)  C       ....
```

```
(0061)          CALL INPUT
(0062)    C
(0063)    C     ASSIGN FIRST TEN CHARACTERS OF SPECIES NAME TO THE ARRAY USED
(0064)    C     BY THE PLOTTING PROGRAM.
(0065)    C
(0066)          DO 10 I=1,NSPEC
(0067)             CALL STRMOV( AAA(1,I), 1, 10, SPNAM(1,I), 11 )
(0068)       10 CONTINUE
(0069)
(0070)
(0071)          IPLOT = 0
(0072)          KLAST = 1
(0073)          NYR1 = NYEAR+1
(0074)          KTIMES = 1
(0075)          N3 = NSPEC+3
(0076)          DO 20 IVA=1,NYR1
(0077)             DO 20 IVS=1,N3
(0078)                A(IVA,IVS) = 0.
(0079)       20 CONTINUE
(0080)          CALL RANSEE
(0081)    C     .....
(0082)    C     .....PLOT SIZE IS ONE-FIFTH HECTARE.
(0083)    C     .....
(0084)    C     .....SOILQ - THE MAXIMUM BIOMASS RECORDED FOR FORESTS IN THE AREA
(0085)    C     .....THE MAXIMUM LIVE ABOVE-GROUND BIOMASS POSSIBLE IS
(0086)    C     .....1000 TONS/HECTARE
(0087)          SOILQ = 100000.
(0088)    C     .....
(0089)    C     .....TGI - TEMPERATURE GROWTH INDEX
(0090)    C     .....
(0091)    C     .....
(0092)    C     .....NSPEC - NUMBER OF SPECIES FOR SIMULATION
(0093)    C     .....
(0094)       30 CONTINUE
(0095)          CALL PLOTIN (IPLOT)
(0096)          WRITE (6,40) IPLOT,NYEAR
(0097)       40 FORMAT (/,15H  PLOT NUMBER  ,I4,24H TOTAL LENGTH OF RUN IS ,
(0098)         +  I5,6H YEARS////////)
(0099)          KYR = 0
(0100)          CALL OUTPUT (KYR,IPLOT)
(0101)          DO 70 JJ=1,KTIMES
(0102)             CALL INIT
(0103)             DO 60 I=1,NYEAR
(0104)                KYR = I
(0105)          NCT = NCT+1
(0106)          IF(NCT .EQ. 2) GO TO 42
(0107)          CALL GGNORD(12,13,Z)
(0108)          GO TO 44
(0109)       42 Z(1) = Z(2)
(0110)          NCT = 0
(0111)       44 TGI=TGII+SD*Z(1)
(0112)    C             TGI = TGII
(0113)                  CALL SELECT
(0114)                  CALL KILL (KYR)
(0115)                   IF(IPERT.NE.0.AND.MOD(KYR,INT).EQ.0) CALL DISTRB(KYR)
(0116)                   IF (IPERT.NE.0.AND.  KYR.EQ.1) CALL DISTRB(KYR)
(0117)       45          CALL BIRTH (KYR)
(0118)                  CALL GROW(KYR)
(0119)                  CALL OUTPUT (KYR,IPLOT)
```

```
(0120)      50        CALL PLTREE (KYR, IPLOT)
(0121)      60     CONTINUE
(0122)      70  CONTINUE
(0123)         IF (IPLOT.NE.KLAST) GO TO 30
(0124)         ZNYR = KLAST
(0125)         DO 110 IV1=1, NYR1
(0126)            TIMEX = IV1-1
(0127)  C         WRITE (7,80) TIMEX
(0128)      80 FORMAT (2E10.3)
(0129)            DO 100 IV2=1, N3
(0130)               A(IV1, IV2) = A(IV1, IV2)/ZNYR
(0131)  C            WRITE (7,80) A(IV1, IV2)
(0132)     100    CONTINUE
(0133)     110 CONTINUE
(0134)  C
(0135)  C      WRITE INFORMATION NEEDED FOR THE PLOT TO FILE TAPE8.
(0136)  C      TAPE8 MAY BE EXAMINED OR THE PLOT PROGRAM APLOT MAY
(0137)  C      BE RUN.
(0138)  C
(0139)  C      WRITE (8,120) NYEAR, NSPEC
(0140)     120 FORMAT (2I8)
(0141)  C      WRITE (8,150) ((SPNAM(I,J), I=1,5), J=1, NSPEC)
(0142)     150 FORMAT (5A4)
(0143)         NNY = NYEAR+1
(0144)         DO 140 I=1, NNY
(0145)  C         WRITE (8,130) (A(I,J), J=1, NSPEC)
(0146)     130 FORMAT (15F8.3)
(0147)     140 CONTINUE
(0148)         CALL EXIT
(0149)         END
```

```
(0001)         SUBROUTINE ADREG(KYR)
(0002)         COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),KSPRT(50),NEWTR(50)
(0003)        1,SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
(0004)   CQS
(0005)   CQS    COMMON /PARAM/ AAA(100,3),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
(0006)          COMMON /PARAM/ AAA(8,100),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
(0007)        1,AGEMX(50),Q(50),SPRTND(50),SPRTMN(50),SPRTMX(50),KTIME(50),A1(50)
(0008)        2,A2(50),BB(50),BC(50),C(50),WMIN(50),IREQ(50,4),DBHMX(50),B1(50),
(0009)        3B4(50),HMAX(50),DRANGE(50)
(0010)          COMMON /CONST/ NSPEC,SOILQ,PMS,TGI,TGII,SD,IQEOG
(0011)          COMMON /RAN/ YFL
(0012)          COMMON /DEAD/ NOGRO(700)
(0013)          COMMON /COUNT/ NTOT,NYEAR
(0014)          COMMON /SEED/ USEED(13)
(0015)          INTEGER USEED
(0016)          REAL LA
(0017)   C      .....
(0018)   C      ..... ADVANCE REGENERATION SUBROUTINE (ADREG) DIFFERS FROM GROW IN THAT
(0019)   C      ..... ONLY SHADE TOLERANT CONIFERS ARE ABLE TO GROW.  THIS ROUTINE IS
(0020)   C      ..... CALLED AFTER  WINDTHROWS
(0021)   C      .....
(0022)   C      .....EACH TREE IS REQUIRED TO ADD A 1.0 MM GROWTH RING EACH YEAR
(0023)   C           OTHERWISE THAT TREE IS SUBJECTED TO A POTENTIAL FOR SLOW-
(0024)   C           GROWTH RELATED MORTALITY (SUBROUTINE KILL)
(0025)   C      .....
(0026)          IF (NTOT.EQ.0) RETURN
(0027)          TINC = .1
(0028)          PHI = 1.
(0029)   C      .....
(0030)   C      .....CALCULATE TOTAL NUMBER OF TREES
(0031)   C      .....
(0032)   C      .....
(0033)   C      .....SUM LEAF AREA OF ALL TREES THAT ARE OF APPROXIMATELY
(0034)   C      .....THE SAME HEIGHT
(0035)   C      .....
(0036)          DO 10 I=1,700
(0037)      10 NOGRO(I) = 0
(0038)          DO 20 I=1,1000
(0039)      20 SUMLA(I) = 0.
(0040)          SBIO = 0.
(0041)           IF (NTOT .GT. 700)  CALL ERR
(0042)          DO 50 K=1,NTOT
(0043)             I = NCODE(K)
(0044)   C      .....
(0045)   C      .....CALCULATE STAND BIOMASS, FOLIAGE BIOMASS IN KG, LEAF AREA
(0046)   C           INDEX
(0047)   C      .....
(0048)   C         LA IS THE LEAF AREA (SQ. M) FOR PSME FROM SAPWOOD AREA
(0049)   C
(0050)                LA=(256.*ALOG(DBH(K))-639.)*2.5
(0051)             IF (I.NE.6) GO TO 30
(0052)             HT=137.+B2(6)*DBH(K)-B3(6)*DBH(K)**2
(0053)             SBIO=SBIO+.02+2.09*DBH(K)**2*(HT/100.)/100.-.0015*(DBH(K)**2*
(0054)           1 HT/100.)**2
(0055)             FBIO=3.2+1.89*ALOG(DBH(K))
(0056)              GO TO 31
(0057)      30     SBIO = SBIO+EXP(A1(I)+BB(I)*ALOG(DBH(K)))
(0058)              FBIO=EXP(A2(I)+BC(I)*ALOG(DBH(K)))
(0059)      31      IF(DBH(K).GE.50.)FBIO=LA*(1/C(16))*DRANGE(I)
```

```
(0060)    35        SBIO = SBIO+FBIO
(0061)  C       .....
(0062)  C       .....HEIGHT PROFILE IS CALCULATED IN .1 METER UNITS
(0063)  C       .....
(0064)     40     HIHT = (137+B2(I)*DBH(K)-B3(I)*DBH(K)**2)/10.+1.
(0065)            IF (HIHT.GT.1000) GO TO 150
(0066)            IHT=HIHT
(0067)             IF(I.EQ.5.OR.I.EQ.6.OR.I.EQ.7.OR.I.EQ.17.OR.I.EQ.21)GO TO 45
(0068)            SUMLA(IHT) = SUMLA(IHT)+C(I)*FBIO/5000.
(0069)           GO TO 50
(0070)     45     SUMLA(IHT)=SUMLA(IHT) + C(I)*FBIO/4000.
(0071)     50  CONTINUE
(0072)         DO 60 J=1,999
(0073)            J1 = 1000-J
(0074)            SUMLA(J1) = SUMLA(J1)+SUMLA(J1+1)
(0075)     60  CONTINUE
(0076)  C       .....
(0077)  C       .....CALCULATE AMOUNT OF GROWTH FOR EACH TREE
(0078)  C       .....
(0079)         NG = 1
(0080)         DO 140 J=1,NTOT
(0081)            I = NCODE(J)
(0082)            IF (ITOL(I) .NE.  5) GO TO 140
(0083)  C       .....
(0084)  C       .....CALCULATE MOISTURE - GROWTH INDEX.
(0085)  C       .....
(0086)            GO TO (80,90,80,80,90,70,90,90,70,90,80,90,80,90,70,90,90,80,80
(0087)         1    ,80,90), I
(0088)  C       .....MOIST SITE SPECIES
(0089)     70     V = WMIN(I)/2.
(0090)            WATDEX = (PMS+2.)*(WMIN(I)-PMS)**V/(2.*WMIN(I)**V)
(0091)            GO TO 100
(0092)  C       .....INTERMEDIATE SITE SPECIES
(0093)     80     V = (WMIN(I)-1.)/9.
(0094)            WATDEX = (PMS+8.)*(WMIN(I)-PMS)**V/(9.*(WMIN(I)-1.)**V)
(0095)            GO TO 100
(0096)  C       .....DRY SITE SPECIES
(0097)     90     V = (WMIN(I)-5.)/15.
(0098)            WATDEX = (PMS+10.)*(WMIN(I)-PMS)**V/(15.*(WMIN(I)-5.)**V)
(0099)    100     HT = 137+B2(I)*DBH(J)-B3(I)*DBH(J)**2
(0100)    102     CONTINUE
(0101)            IHT = HT/10.+2.
(0102)    104     CONTINUE
(0103)            SLAR = SUMLA(IHT)
(0104)            AL = PHI*EXP(-SLAR*.26)
(0105)            LA=(256.*ALOG(DBH(J))-639.)*2.5
(0106)            FBIO=EXP(A2(I)+BC(I)*ALOG(DBH(J)))
(0107)            IF(I.EQ.6)FBIO=3.20+1.89*ALOG(DBH(J))
(0108)            IF(DBH(J).GE.50.) FBIO=LA*(1./C(16))*DRANGE(I)
(0109)    120     A = (1.-(DBH(J)*HT)/(DBHMX(I)*HMAX(I)))
(0110)            B= DBH(J)*B1(I)*FBIO**B4(I)
(0111)            CC = (274+3.*B2(I)*DBH(J)**2-4.*B3(I)*DBH(J)**3)
(0112)            D= (1.-SBIO/SOILQ)*4
(0113)            TEGD = (TGI-DMIN(I))*(DMAX(I)-TGI)/(DMAX(I)-DMIN(I))**2
(0114)            DNC = (A * B / CC) * D * TEGD *WATDEX
(0115)            DINC = (1.-EXP(-32.846*(AL-0.025)))*DNC
(0116)            IF (DBH(J) .LT.  DBHMX(I)) GO TO 121
(0117)            DINC = 0.0
(0118)    121     CONTINUE
```

```
C      .....
C      .....CHECK INCREMENT LESS THAN 1.0 MM REQUIRED GROWTH .
C      .....
C      ..... WRITE OUT DIAMETER INCREMENT FOR PSME
C
         IF (I .NE. 16) GO TO 125
         IF (DBH(J) .LE. 86. .OR. DBH(J) .GT. 165.) GO TO 125
         WRITE (9,122) DINC,KYR
  122    FORMAT (1X,F9.4,5X,I5)
  125    CONTINUE
          IF (DINC.GE.TINC) GO TO 130
          IF (DINC.LT.0.) DINC = 0.
          NOGRO(NG) = J
          NG = NG+1
  130     DBH(J) = DBH(J)+DINC
  140 CONTINUE
      RETURN
  150 WRITE (6,160)
  160 FORMAT (19H1 IHT EXCEEDED 1000)
       STOP
      END
```

```
(0001)          SUBROUTINE BIRTH (KYR)
(0002)          COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),KSPRT(50),NEWTR(50)
(0003)         1,SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
(0004)          COMMON /PARAM/ AAA(8,100),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
(0005)         1,AGEMX(50),G(50),SPRTND(50),SPRTMN(50),SPRTMX(50),KTIME(50),A1(50)
(0006)         2,A2(50),BB(50),BC(50),C(50),WMIN(50),IREG(50,4),DBHMX(50),B1(50),
(0007)         3B4(50),HMAX(50),DRANGE(50)
(0008)          COMMON /CONST/ NSPEC,SOILG,PMS,TGI,TGII,SD,IGEOG
(0009)          COMMON /RAN/ YFL
(0010)          COMMON /DEAD/ NOGRO(700)
(0011)          COMMON /COUNT/ NTOT,NYEAR,IPERT,INT,IN,PMORT
(0012)          COMMON /SEED/ USEED(13)
(0013)          INTEGER USEED
(0014)          REAL LA
(0015)  C       .....
(0016)  C       .....SAPLINGS ENTER THE PLOT AT AVERAGE SIZE OF 10.0 CM DBH
(0017)  C       .....
(0018)           IF(KYR.LE.20) GO TO 3
(0019)           IF (NTOT.GT.200. .AND. MOD(KYR,10) .EQ. 0) GO TO 120
(0020)      3    CONTINUE
(0021)          SIZE = 10.0
(0022)  C       .....
(0023)  C       .....SELECT A SPECIES FROM 1 TO 3 TIMES
(0024)  C       .....
(0025)  C       ....ADD UP NUMBER OF ABAM AND TSHE OF SIZE 10 TO 20 CM SO THAT
(0026)  C       .... A RESTRICION CAN BE PUT ON THE NUMBER OF BIRTHS.
(0027)  C       ......
(0028)            NABAM = 0
(0029)            NTSHE = 0
(0030)            DO 9 K = 1,NTOT
(0031)              KK=NCODE(K)
(0032)              IF (KK.NE.1) GO TO 5
(0033)              IF (DBH(K).GE.20. .OR. DBH(K) .LT. 10.) GO TO 5
(0034)              NABAM = NABAM + 1
(0035)      5       CONTINUE
(0036)              IF (KK.NE.19) GO TO 8
(0037)              IF (DBH(K).GE.20. .OR. DBH(K) .LT. 10.) GO TO 8
(0038)              NTSHE = NTSHE + 1
(0039)      8       CONTINUE
(0040)      9       CONTINUE
(0041)          NPLANT = 3.*RANF(6)+1.
(0042)  C       ....
(0043)          DO 100 JK=1,NPLANT
(0044)      10     FBIO = 0.
(0045)  C       .....
(0046)  C       .....CALCULATE BIOMASS (LEAF MASS) FOR EACH SPECIES
(0047)             IF (NTOT.EQ.0) GO TO 40
(0048)             DO 30 K=1,NTOT
(0049)                KK = NCODE(K)
(0050)               LA=(256.0*ALOG(DBH(K))-639.)
(0051)      20       IF(KK.EQ.5.OR.KK.EQ.7.OR.KK.EQ.17.OR.KK.EQ.21) GO TO 25
(0052)             FBIO=EXP(A2(KK)+BC(KK)*ALOG(DBH(K))) *C(KK)/2.5 +FBIO
(0053)              IF(DBH(K).GE.50.) FBIO=FBIO+LA*DRANGE(KK)/2.5
(0054)               GO TO 30
(0055)      25        FBIO=FBIO +EXP(A2(KK)+BC(KK)*ALOG(DBH(K))) *C(KK)/2.0
(0056)               IF(DBH(K).GE.50.) FBIO=FBIO+LA*DRANGE(KK)/2.0
(0057)      30     CONTINUE
(0058)      40     NW = 0
(0059)             XLAI = FBIO/2000.
```

```
0060)            DO 70 J=1,NSPEC
0061)               IF (J.EQ.1 .AND. NABAM .GT. 200) GO TO 70
0062)               IF (J.EQ.19 .AND. NTSHE .GT. 100) GO TO 70
0063)               IF (ISEL(J).NE.1) GO TO 70
0064)               IF (XLAI.LT.3.) GO TO 60
0065)               GO TO (50,50,50,50,50,70,50,50,50,70,50,50,50,70,50,50,70
0066)         1           ,50,50,50,50),J
0067)      50       IF (XLAI.LT.6.) GO TO 60
0068)               GO TO (54,54,54,70,54,54,54,54,54,54,54,54,54,54,54,70,
0069)         1           54,54,54,54,70), J
0070)      54       IF (XLAI .LT. 8.) GO TO 60
0071)               GO TO (58,70,70,58,70,58,70,58,58,58,70,70,70,58,70,58,
0072)         1           58,58,58,58,58), J
0073)      58       IF (XLAI .LT. 10.) GO TO 60
0074)               GO TO (60,60,60,60,60,60,60,70,70,60,60,60,60,60,60,60,60,
0075)         1           70,60,70,60), J
0076)      60       NW = NW+1
0077)               NEWTR(NW) = J
0078)      70    CONTINUE
0079)  C     .....
0080)  C     .....CHECK TO SEE IF THERE ARE ANY NEW TREES
0081)  C     .....
0082)            IF (NW.EQ.0) GO TO 90
0083)  C     .....
0084)  C     .....CALCULATE AGE AND DIAMETER FOR NEW TREES
0085)  C     .....
0086)  C     .....
0087)  C     .....DETERMINE THE NUMBER OF SEEDLINGS TO PLANT  0 TO 8
0088)  C     .....
0089)            MPLANT = RANF(9)*8.
0090)  C     .....
0091)  C     .....SELECT SEEDLINGS (PARTICULAR SPECIES)
0092)  C     .....
0093)            NW = NW*RANF(10)+1.0
0094)            NSP = NEWTR(NW)
0095)  C     .....
0096)  C     .....PLANT RANDOM NUMBER OF SEEDLINGS
0097)  C     .....
0098)            DO 80 J=1,MPLANT
0099)               NTOT = NTOT+1
0100)               IF (NTOT.GT.700) CALL ERR
0101)               IAGE(NTOT) = 0
0102)               NCODE(NTOT) = NSP
0103)  C     .....
0104)  C     .....CALCULATE DBH FOR SEEDLINGS
0105)  C     .....
0106)               DBH(NTOT) = SIZE+5.*(1.0-RANF(11))**3
0107)               NTREES(NSP) = NTREES(NSP)+1
0108)      80    CONTINUE
0109)      90    CONTINUE
0110)            CALL SPROUT
0111)  C     .....
0112)  C     .....BIRTH CONTINUED UNTIL LAI .GE. 1.
0113)  C     .....
0114)            XLAI = FBIO/2000.
0115)            IF (XLAI.LT.1.) GO TO 10
0116)     100 CONTINUE
0117)  C     .....
0118)  C     .....INCREMENT AGES
0119)  C     .....
0120)         DO 110  I=1,NTOT
0121)            IAGE(I) = IAGE(I)+1
0122)     110 CONTINUE
0123)     120  CONTINUE
0124)         RETURN
0125)         END
```

```
(0001)          SUBROUTINE DISTRB(KYR)
(0002)          COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),KSPRT(50),
(0003)         1 NEWTR(50),SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
(0004)          COMMON /PARAM/ AAA(8,100),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
(0005)         1,AGEMX(50),G(50),SPRTND(50),SPRTMN(50),SPRTMX(50),KTIME(50),A1(50)
(0006)         2,A2(50),BB(50),BC(50),C(50),WMIN(50),IREG(50,4),DBHMX(50),B1(50),
(0007)         3B4(50),HMAX(50),DRANGE(50)
(0008)   CQS
(0009)          COMMON /CONST/ NSPEC,SOILQ,PMS,TQI,TQII,SD,IGEOG
(0010)          COMMON /COUNT/ NTOT,NYEAR,IPERT,INT,IN,PMORT,FI
(0011)          COMMON /SEED/ USEED(13)
(0012)          INTEGER USEED
(0013)          IF (IPERT.EQ.0) RETURN
(0014)          IF (IPERT.EQ.1) WRITE(6,16)INT
(0015)          IF (IPERT.EQ.2) WRITE(6,17)INT
(0016)          IF (IPERT.EQ.3) WRITE(6,18)INT
(0017)     16   FORMAT (1HO,11H FIRE EVERY,I5,6H YEARS)
(0018)     17   FORMAT (1HO,17H WINDSTORMS EVERY,I5,6H YEARS)
(0019)     18   FORMAT (1HO,13H CLEARCUTS ON,I5,9H ROTATION)
(0020)          IF(IPERT .NE. 1) GO TO 65
(0021)   C
(0022)   C      FIRE
(0023)   C
(0024)          DO 60 K=1,NTOT
(0025)             I=NCODE(K)
(0026)             P=0.0
(0027)             IF(I.NE.17 OR.I.NE.12 OR.I.NE.14 OR.I NE.16.OR.I NE.8)GO TO 30
(0028)   C
(0029)   C          FIRE TOLERANT SPECIES HAVE THE FOLLOWING PROBABILITY
(0030)   C                OF DYING IN A FIRE
(0031)   C
(0032)             P=(EXP(-.00255*DBH(K)))*FI
(0033)             GO TO 40
(0034)     30      P=(EXP(-.00053*DBH(K)))*FI
(0035)     40      IF (RANF(2) .GT. P) GO TO 60
(0036)             NTREES(I)=NTREES(I)-1
(0037)             IF(DBH(K).GT.SPRTMN(I).AND.DBH(K).LT.SPRTMX(I))KSPRT(I)=-1
(0038)                  IF (PMORT .NE. 9) GO TO 50
(0039)                  WRITE (9,45) NCODE(K),DBH(K),KYR
(0040)     45           FORMAT (3X,I3,F6.2,I4)
(0041)     50           CONTINUE
(0042)             DBH(K)=-1
(0043)     60      CONTINUE
(0044)     65    CONTINUE
(0045)           IF (IPERT .NE. 2) GO TO 98
(0046)   C
(0047)   C        LIGHT WINDSTORMS BASED ON THE TAR CREEK DATA (OF J. FRANKLIN)
(0048)   C
(0049)   C        DO 80 K =1,NTOT
(0050)   C            I=NCODE(K)
(0051)   C            IF (I.EQ.16  .OR. I.EQ.13 .OR. I.EQ.12
(0052)   C     1           .OR. I.EQ.14 .OR. I.EQ.4) GO TO 70
(0053)   C            IF (I.EQ.5 .OR. I.EQ.6 .OR. I.EQ.7 .OR. I.EQ.17 .OR.
(0054)   C     1          I EQ.18 .OR. I.EQ.21 .OR. I.EQ.9 .OR. I.EQ.8)  GO TO 74
(0055)   C            IF (DBH(K) .GT. 60.) GO TO 68
(0056)   C             P = .15 -.001 * DBH(K)
(0057)   C             GO TO 79
(0058)   C  68        P = .07
(0059)   C             GO TO 79
```

```
0060)  C  70        IF (DBH(K) .GT. 100.) GO TO 72
0061)  C             P = .13 - .001 * DBH(K)
0062)  C             GO TO 79
0063)  C  72        P = .03
0064)  C             GO TO 79
0065)  C  74        IF (DBH(K) .GT. 100.) GO TO 78
0066)  C             P = .30 - .02 * DBH(K)
0067)  C             GO TO 79
0068)  C  78        P = .18
0069)  C
0070)  C  79         IF(RANF(3) .GT.P) GO TO 80
0071)  C            NTREES(I) = NTREES(I)-1
0072)  C            IF(DBH(K).GT. SPRTMN(I).AND.DBH(K).LT.SPRTMX(I))
0073)  C     1       KSPRT(I)=-1
0074)  C            DBH(K)=-1
0075)    80     CONTINUE
0076)    90     CONTINUE
0077)  CATASTROPHIC WIND
0078)          DO 96 K=1,NTOT
0079)  C           SPRUCE & HEMLOCKS ARE WIND INTOLERANT
0080)              I = NCODE(K)
0081)              IF (I.EQ.11 .OR. I .EQ.19 .OR. I.EQ.20) GO TO 92
0082)                  WRITE(6,91) DBH(K),K
0083)    91            FORMAT ( F10.3,I5)
0084)              P=(1-(EXP(-.00255*DBH(K)))+0.6)*FI
0085)              GO TO 94
0086)    92        P=(1-(EXP(-.00053*DBH(K)))+0.9)*FI
0087)    94        IF(RANF(3).GT.P) GO TO 96
0088)              IF(DBH(K).GT. SPRTMN(I) .AND. DBH(K).LT.SPRTMX(I))
0089)         1       KSPRT(I)=-1
0090)                     IF (PMORT .NE. 9) GO TO 95
0091)                     WRITE (9,45) NCODE(K),DBH(K),KYR
0092)    95               CONTINUE
0093)              DBH(K)=-1
0094)    96     CONTINUE
0095)    98    IF (IPERT.NE.3) GO TO 110
0096)  C
0097)  C         CLEARCUTS
0098)  C
0099)          DO 100 K=1,NTOT
0100)               NTREES(I)=NTREES(I)-1
0101)                     IF (PMORT .NE. 9) GO TO 99
0102)                     WRITE (9,45) NCODE(K),DBH(K),KYR
0103)    99               CONTINUE
0104)               DBH(K)=-1
0105)    100       CONTINUE
0106)    110   CONTINUE
0107)    148   K1=0
0108)          DO 150 K=1,NTOT
0109)             IF(DBH(K).LT.0.) GO TO 150
0110)             K1=K1+1
0111)             DBH(K1)=DBH(K)
0112)             IAGE(K1)=IAGE(K)
0113)             NCODE(K1)=NCODE(K)
0114)    150      CONTINUE
0115)    160   CONTINUE
0116)          NTOT=K1
0117)          IF (IPERT .NE. 3) GO TO 180
0118)  C       AFTER CLEARCUT PLANT PSEUDOTSUGA MENZIESII (OTHER SPECIES COULD BE
```

```
(0119)  C            PLANTED BY MAKING CHANGES IN THE "170" LOOP)
(0120)  C
(0121)          DO 170 J = 1,50
(0122)               NTOT=NTOT + 1
(0123)               IAGE(NTOT)=0
(0124)               NCODE(NTOT)=16
(0125)               DBH(NTOT)= 10.  + 5.  *(1.0-RANF(11))**3
(0126)               NTREES(16) = NTREES(16) + 1
(0127)     170   CONTINUE
(0128)  CC       INCREASE YEAR COUNT BY 30 TO MAKE UP LOSS SINCE THESE TREES
(0129)  CC           WERE INTRODUCED AT 10 CM DBH AFTER THE CLEARCUT.
(0130)  CC
(0131)          KYR=KYR+30
(0132)  CC
(0133)  CC
(0134)  CC       CAUSE ADVANCE REGENERATION BY CALLING SUBROUTINE ADREG AFTER WIND
(0135)          IF (IPERT.NE.2) GO TO 200
(0136)  CC
(0137)     180   DO 190 IT=1,3
(0138)               CALL ADREG(KYR)
(0139)     190   CONTINUE
(0140)     200   CONTINUE
(0141)  CC       SINCE TREES ARE INTRODUCED AT 10 CM DBH, LET MODEL GROW TREES
(0142)  CC           FOR 30 YEARS TO MAKE UP LAG IN GROWTH.
(0143)  CC
(0144)           IF (IPERT.NE.1 .OR.  IPERT .NE.  2) GO TO 220
(0145)           DO 210 I=1,30
(0146)               CALL KILL(KYR)
(0147)               CALL GROW(KYR)
(0148)     210       KYR=KYR+1
(0149)     220    CONTINUE
(0150)          RETURN
(0151)          END
```

```
(0001)          SUBROUTINE ERR
(0002)          WRITE (6,10)
(0003)       10 FORMAT (37H1 THE NUMBER OF TREES HAS EXCEEDED 800)
(0004)          STOP
(0005)          END
```

```
(0001)          SUBROUTINE GGNORD (NSEED1,NSEED2,Z)
(0002)          DIMENSION Z(1)
(0003)          DATA PI2/0.62831853E01/
(0004)          K = 0
(0005)          A1 = RANF(NSEED1)
(0006)          A2 = RANF(NSEED2)
(0007)          K = K+1
(0008)          Z(K) = SQRT(-.2E01*ALOG(A1))*SIN(PI2*A2)
(0009)          K = K+1
(0010)          Z(K) = SQRT(-0.2E01*ALOG(A1))*COS(PI2*A2)
(0011)          RETURN
(0012)          END
```

```
0001)         SUBROUTINE GROW(KYR)
0002)         COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),ASPRT(50),NEWTR(50),
0003)        1,SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
0004)   CQS
0005)   CQS    COMMON /PARAM/ AAA(100,3),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
0006)          COMMON /PARAM/ AAA(8,100),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
0007)        1,AGEMX(50),G(50),SPRTND(50),SPRTMN(50),SPRTMX(50),KTIME(50),A1(50)
0008)        2,A2(50),BB(50),BC(50),C(50),WMIN(50),IREQ(50,4),DBHMX(50),B1(50),
0009)        3B4(50),HMAX(50),DRANGE(50)
0010)          COMMON /CONST/ NSPEC,SOILQ,PMS,TGI,TGII,SD,IQEOG
0011)          COMMON /RAN/ YFL
0012)          COMMON /DEAD/ NOGRO(700)
0013)          COMMON /COUNT/ NTOT,NYEAR
0014)          COMMON /SEED/ USEED(13)
0015)          INTEGER USEED
0016)          REAL LA
0017)   C      .....
0018)   C      .....EACH TREE IS REQUIRED TO ADD A 1.0 MM GROWTH RING EACH YEAR
0019)   C           OTHERWISE THAT TREE IS SUBJECTED TO A POTENTIAL FOR SLOW-
0020)   C           GROWTH RELATED MORTALITY (SUBROUTINE KILL)
0021)   C      .....
0022)          IF (NTOT.EQ.0) RETURN
0023)          TINC = .1
0024)          PHI = 1.
0025)   C      .....
0026)   C      .....CALCULATE TOTAL NUMBER OF TREES
0027)   C      .....
0028)   C      .....
0029)   C      .....SUM LEAF AREA OF ALL TREES THAT ARE OF APPROXIMATELY
0030)   C      .....THE SAME HEIGHT
0031)   C      .....
0032)          DO 10 I=1,700
0033)       10 NOGRO(I) = 0
0034)          DO 20 I=1,1000
0035)       20 SUMLA(I) = 0.
0036)          SBIO = 0.
0037)           IF (NTOT .GT. 700)  CALL ERR
0038)          DO 50 K=1,NTOT
0039)             I = NCODE(K)
0040)   C      .....
0041)   C      .....CALCULATE STAND BIOMASS, FOLIAGE BIOMASS IN KG, LEAF AREA
0042)   C           INDEX
0043)   C      .....
0044)   C          LA IS THE LEAF AREA (SQ. M) FOR PSME FROM SAPWOOD AREA
0045)                LA=(256.*ALOG(DBH(K))-639.)*2.5
0046)             IF (I.NE.6) GO TO 30
0047)             HT=137.+B2(6)*DBH(K)-B3(6)*DBH(K)**2
0048)             SBIO=SBIO+.02+2.09*DBH(K)**2*(HT/100.)/100.-.0015*(DBH(K)**2*
0049)          1  HT/100.)**2
0050)             FBIO=3.2+1.89*ALOG(DBH(K))
0051)              GO TO 31
0052)       30     SBIO = SBIO+EXP(A1(I)+BB(I)*ALOG(DBH(K)))
0053)              FBIO=EXP(A2(I)+BC(I)*ALOG(DBH(K)))
0054)    31        IF(DBH(K).GE.50.)FBIO=LA*(1/C(16))*DRANGE(I)
0055)     35        SBIO = SBIO+FBIO
0056)   C      .....
0057)   C      .....HEIGHT PROFILE IS CALCULATED IN .1 METER UNITS
0058)   C      .....
0059)       40     HIHT = (137+B2(I)*DBH(K)-B3(I)*DBH(K)**2)/10.+1.
```

```
(0060)            IF (HIHT.GT.1000) GO TO 150
(0061)            IHT=HIHT
(0062)             IF(I.EQ.5.OR.I.EQ.6.OR.I.EQ.7.OR.I.EQ.17.OR.I.EQ.21)GO TO 45
(0063)            SUMLA(IHT) = SUMLA(IHT)+C(I)*FBIO/5000.
(0064)           GO TO 50
(0065)      45    SUMLA(IHT)=SUMLA(IHT) + C(I)*FBIO/4000.
(0066)      50 CONTINUE
(0067)         DO 60 J=1,999
(0068)            J1 = 1000-J
(0069)            SUMLA(J1) = SUMLA(J1)+SUMLA(J1+1)
(0070)      60 CONTINUE
(0071)   C      .....
(0072)   C      .....CALCULATE AMOUNT OF GROWTH FOR EACH TREE
(0073)   C      .....
(0074)         NG = 1
(0075)         DO 140 J=1,NTOT
(0076)            I = NCODE(J)
(0077)   C      .....
(0078)   C      .....CALCULATE MOISTURE - GROWTH INDEX.
(0079)   C      .....
(0080)            GO TO (80,90,80,80,90,70,90,90,70,90,80,90,80,90,70,90,90,80,80
(0081)        1   ,80,90), I
(0082)   C      .....MOIST SITE SPECIES
(0083)      70    V = WMIN(I)/2.
(0084)             WRITE (6,72) I,WMIN(I),V
(0085)      72     FORMAT (6H  I=  ,I3,6H WMIN= ,F6.2,6H  V=  ,F6.2)
(0086)            WATDEX = (PMS+2.)*(WMIN(I)-PMS)**V/(2.*WMIN(I)**V)
(0087)              WRITE (6,73) WATDEX
(0088)      73      FORMAT ( 8H WATDEX= ,F6.2)
(0089)            GO TO 100
(0090)   C      .....INTERMEDIATE SITE SPECIES
(0091)      80    V = (WMIN(I)-1.)/9.
(0092)            WATDEX = (PMS+8.)*(WMIN(I)-PMS)**V/(9.*(WMIN(I)-1.)**V)
(0093)            GO TO 100
(0094)   C      .....DRY SITE SPECIES
(0095)      90    V = (WMIN(I)-5.)/15.
(0096)            WATDEX = (PMS+10.)*(WMIN(I)-PMS)**V/(15.*(WMIN(I)-5.)**V)
(0097)     100    HT = 137+B2(I)*DBH(J)-B3(I)*DBH(J)**2
(0098)     102    CONTINUE
(0099)            IHT = HT/10.+2.
(0100)     104    CONTINUE
(0101)            SLAR = SUMLA(IHT)
(0102)            AL = PHI*EXP(-SLAR*.26)
(0103)            LA=(256.*ALOG(DBH(J))-639.)*2.5
(0104)            FBIO=EXP(A2(I)+BC(I)*ALOG(DBH(J)))
(0105)            IF(I.EQ.6)FBIO=3.20+1.89*ALOG(DBH(J))
(0106)            IF(DBH(J).GE.50.) FBIO=LA*(1./C(16))*DRANGE(I)
(0107)     120    A = (1.-(DBH(J)*HT)/(DBHMX(I)*HMAX(I)))
(0108)            B= DBH(J)*B1(I)*FBIO**B4(I)
(0109)            CC = (274+3.*B2(I)*DBH(J)**2-4.*B3(I)*DBH(J)**3)
(0110)            D= (1.-SBIO/SOILG)*4
(0111)            TEGD = (TGI-DMIN(I))*(DMAX(I)-TGI)/(DMAX(I)-DMIN(I))**2
(0112)            DNC = (A * B / CC) * D * TEGD *WATDEX
(0113)            DINC = (1.-EXP(-20.467*(AL-0.025)))*DNC
(0114)   C      .....
(0115)   C      .....
(0116)   C      .....CHECK FOR PS CURVE TYPE - PONDEROSA PINE
(0117)   C      .....
(0118)            IF (ITOL(I).EQ.1) DINC = (1.0-EXP(-23.026*(AL-0.30)))*DNC
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0119)           IF(ITOL(I).EQ.1 .AND. AL.LT.0.3) DINC=0.
0120)  C        .....
0121)  C        .....CHECK FOR PS CURVE TYPE - HARDWOODS
0122)  C        .....
0123)             IF (ITOL(I).EQ.2) DINC = (1.0-EXP(-9.695*(AL-0.025)))*DNC
0124)  C        .....
0125)  C        .....CHECK FOR PS CURVE TYPE - TOLERANT CONIFERS
0126)             IF (ITOL(I).EQ.4) DINC = (1.-EXP(-32.846*(AL-0.025)))*DNC
0127)             IF (ITOL(I).EQ.5) DINC = (1.-EXP(-40.0*(AL-0.025)))*DNC
0128)             IF (DBH(J) .LT. DBHMX(I)) GO TO 121
0129)             DINC = 0.0
0130)   121      CONTINUE
0131)  C        .....
0132)  C        .....CHECK INCREMENT LESS THAN 1.0 MM REQUIRED GROWTH
0133)  C        .....
0134)  C        ..... WRITE OUT DIAMETER INCREMENT FOR PSME
0135)  C
0136)           IF (I .NE. 16) GO TO 125
0137)           IF (DBH(J) .LE. 86. .OR. DBH(J) .GT. 165.) GO TO 125
0138)           IF (PMORT.NE.2) GO TO 125
0139)           WRITE (9,122) DINC,KYR
0140)    122    FORMAT (1X,F9.4,5X,I5)
0141)    125    CONTINUE
0142)            IF (DINC.GE.TINC) GO TO 130
0143)            IF (DINC.LT.0.) DINC = 0.
0144)            NOGRO(NG) = J
0145)            NG = NG+1
0146)    130     DBH(J) = DBH(J)+DINC
0147)    140  CONTINUE
0148)         RETURN
0149)    150  WRITE (6,160)
0150)    160  FORMAT (19H1 IHT EXCEEDED 1000)
0151)          STOP
0152)         END
```

```
0001)         SUBROUTINE INIT
0002)         COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),KSPRT(50),NEWTR(50)
0003)        1,SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
0004)         COMMON /CONST/ NSPEC,SOILQ,PMS,TGI,TGII,SD,IQEOG
0005)         COMMON /DEAD/ NOGRO(700)
0006)         DO 10 I=1,NSPEC
0007)            NOGRO(I) = 0
0008)            KSPRT(I) = 1
0009)      10 CONTINUE
0010)         NSPE1 = NSPEC+1
0011)         DO 20 I=NSPE1,700
0012)            NOGRO(I) = 0
0013)      20 CONTINUE
0014)   CQS   RND IS THE RANDOM NUMBER GENERATOR ON THE PRIME
0015)          CALL R=RND(1)
0016)         RETURN
0017)         END
```

```
      SUBROUTINE INPUT
      COMMON /PARAM/ AAA(8,100),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
     1,AGEMX(50),Q(50),SPRTND(50),SPRTMN(50),SPRTMX(50),KTIME(50),A1(50)
     2,A2(50),BB(50),BC(50),C(50),WMIN(50),IREQ(50,4),DBHMX(50),B1(50),
     3B4(50),HMAX(50),DRANGE(50)
      COMMON /CONST/ NSPEC,SOILQ,PMS,TQI,TQII,SD,IGEOG
       COMMON /COUNT/ NTOT,NYEAR,IPERT,INT,IN,PMORT,FI
      DIMENSION NSELCT(50)
      READ (5,10) NSPEC,(NSELCT(I),I=1,NSPEC)
   10 FORMAT (40I2)
      READ (5,20) TQII,SD,PMS,IGEOG,NYEAR,IPERT,INT,PMORT,IN
   20 FORMAT (F5.1,2F3.0,I1,5I4)
C
C ---------------------------------------------------------------------
C     NYEAR=LENGTH OF THE MODEL RUN IN YEARS
C     IPERT= DISTURBANCE TYPE
C        0 NONE
C        1 FIRE
C        2 WINDTHROW
C        3 CLEARCUT
C     INT=INTERVAL OF DISTURBANCE  IN YEARS
C    PMORT - IF EQUAL TO
C          2 = PRINT OUT DIAMETER INCREMENT OF DOUGLAS FIR ON YEARLY BASIS
C          7 = PRINT OUT STAND STRUCTURE AT YEAR 700 FOR INPUT INTO NEXT
C                RUN OF THE MODEL
C          9 = PRINT OUT MORTALITY INFORMATION: SPECIES, DBH AND YEAR DIED
C                FOR INPUT INTO DECAY MODEL - SEE GRAHAM, R. 1982. PH.D. THESIS
C                AT OREGON STATE UNIVERSITY, P. 112.
C
C     IN=READ IN STAND STRUCTURE IF NOT 0
C       = NUMBER OF TREES TO BE READ IN (THE DATA IS AT THE END OF THE
C         FILE SUCDAT)
C
C ---------------------------------------------------------------------
       READ (5,25) FI
   25  FORMAT (F5.2)
C      FI= FIRE OR WIND INTENSITY (0<FI<=1)
C
       DO 40 J=1,NSPEC
          READ (5,30) (AAA(I,J),I=1,5),DMAX(J),DMIN(J),B3(J),B2(J),ITOL(J
     1    ),AGEMX(J),SPRTND(J),SPRTMN(J),SPRTMX(J),KTIME(J),NUM,A1(J),A2
     2    (J),BB(J),BC(J),C(J),WMIN(J),(IREQ(J,I),I=1,4),DBHMX(J),B1(J),
     3    HMAX(J),B4(J),DRANGE(J)
   30 FORMAT (5A4 ,6X,F4.0,1X,2F4.0,F5.0,I1,F4.0,7X,F2.0,2F4.0,I4,3X,I2/
     1F7.4,F6.3,F7.4,F6.4,1X,F4.1,F3.0,4I1/F4.0,F5.0,F5.0,F3.1,F6.3)

   40 CONTINUE
C
C       FOR "NONSTRESSED" SITES USE HEIGHT PARAMETERS DERIVED FROM
C       REGRESSION ANALYSIS.
C
       IF(TQII .GT. 60.0 .AND. PMS .LT. 15.) GO TO 45
           B2(16)=72.34
           B3(16)=0.22
           B2(19)=75.97
           B3(19)=0.27
   45    CONTINUE
      WRITE (6,50)
   50 FORMAT (1H1,1H ,6X,7HSPECIES,11X,11HDEGREE DAYS,2X,11HHEIGHT PARA,
```

```
     12X,4HITOL,2X,5HAGEMX,2X,6HSPRTND,/,26X,3HMAX,3X,3HMIN,4X,2HB3,4X,
     22HB2/)
      DO 70 I=1,NSPEC
         WRITE (6,60) I,(AAA(J,I),J=1,5),DMAX(I),DMIN(I),B3(I),B2(I),
     1    ITOL(I),AGEMX(I),SPRTND(I)
   60 FORMAT (1H ,I2,1X,5A4 ,2X,F4 0,3X,F4.0,1X,F5.2,1X,F6.2,3X,I2,3X,
     1F5.0,4X,F3.0)
   70 CONTINUE
      WRITE (6,80)
   80 FORMAT (////,1H ,6X,7HSPECIES,11X,6HSPRTMN,2X,6HSPRTMX,2X,5HKTIME,
     16X,2HA1,7X,2HA2,7X,2HBB,7X,2HBC,7X,1HC,6X,4HWMIN/)
      DO 100 I=1,NSPEC
         WRITE (6,90) I,(AAA(J,I),J=1,5),SPRTMN(I),SPRTMX(I),KTIME(I),A1
     1    (I),A2(I),BB(I),BC(I),C(I),WMIN(I)
   90 FORMAT (1H ,I2,1X,5A4 ,2X,F4.0,4X,F4.0,2X,I6,6(2X,F7.4))
  100 CONTINUE
      WRITE (6,110)
  110 FORMAT (1H1,1H ,6X,7HSPECIES,16X,4HIREQ,6X,5HDBHMX,6X,2HB1,6X,
     14HHMAX,8X,2HB4,8X,6HDRANGE,/,28X,1H1,2X,1H2,2X,1H3,2X,1H4/)
      DO 130 I=1,NSPEC
         WRITE (6,120) I,(AAA(J,I),J=1,5),(IREQ(I,J),J=1,4),DBHMX(I),B1
     1    (I),HMAX(I),B4(I),DRANGE(I)
  120 FORMAT (1H ,I2,1X,5A4 ,2X,4I3,3X,F5.0,3(2X,F8.1),2X,F8.3)
  130 CONTINUE
      RETURN
      END
```

```
(0001)          SUBROUTINE KILL (KYR)
(0002)          COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),KSPRT(50),NEWTR(50)
(0003)         1,SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
(0004)          COMMON /PARAM/ AAA(8,100),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
(0005)         1,AGEMX(50),Q(50),SPRTND(50),SPRTMN(50),SPRTMX(50),KTIME(50),A1(50)
(0006)         2,A2(50),BB(50),BC(50),C(50),WMIN(50),IREG(50,4),DBHMX(50),B1(50),
(0007)         3B4(50),HMAX(50),DRANGE(50)
(0008)          COMMON /CONST/ NSPEC,SOILQ,PMS,TGI,TGII,SD,IGEOG
(0009)          COMMON /DEAD/ NOGRO(700)
(0010)          COMMON /COUNT/ NTOT,NYEAR,IPERT,INT,IN,PMORT
(0011)          COMMON /SEED/ USEED(13)
(0012)          INTEGER USEED
(0013)          IF (NTOT.EQ.0) RETURN
(0014)          NG = 1
(0015)       10 CONTINUE
(0016)  C       .....
(0017)  C       .....SUPPRESSION MORTALITY
(0018)  C            IS DEPENDENT UPON SPECIES AND SIZE OF TREE
(0019)  C
(0020)  C       .....
(0021)           IF (PMORT .NE. 9 .AND. KYR .NE. 1) GO TO 15
(0022)           WRITE (9,12)
(0023)       12  FORMAT (3X,3H -1,10X,39H DATA FOR DEAD TREES = SPECIES DBH YEAR)
(0024)       15  CONTINUE
(0025)       20 DO 130 K=1,NTOT
(0026)             I = NCODE(K)
(0027)  C       .....CHECK FOR SUPPRESSION
(0028)             IF (NOGRO(NG).NE.K) GO TO 130
(0029)             NG = NG+1
(0030)  C       .....SORT MORTALITY TYPES
(0031)             GO TO (100,80,80,80,50,50,50,60,60,80,80,80,80,30,80,30,50,60,
(0032)         1   100,100,50), I
(0033)  C       .....LONG-LIVED EARLY SERAL SPECIES.
(0034)       30    IF (DBH(K).GT.0.2*DBHMX(I)) GO TO 40
(0035)             P = 0.8866+0.1029/(0.2-1./DBHMX(I))*((DBH(K)-1.)/DBHMX(I))
(0036)             IF (RANF(2).LT.P) GO TO 130
(0037)             GO TO 120
(0038)       40    IF (RANF(2).LT.0.9895) GO TO 130
(0039)             GO TO 120
(0040)  C       .....SHORT-LIVED EARLY SERAL SPECIES.
(0041)       50    IF (RANF(2).LT.0.628) GO TO 130
(0042)             GO TO 120
(0043)  C       .....LONG-LIVED MID SERAL SPECIES.
(0044)       60    IF (DBH(K).GT.0.1*DBHMX(I)) GO TO 70
(0045)             P = 0.96496+0.01294/(0.1-1./DBHMX(I))*(DBH(K)-1.)/DBHMX(I)
(0046)             IF (RANF(2).LT.P) GO TO 130
(0047)             GO TO 120
(0048)       70    P = 0.97556+0.02339*DBH(K)/DBHMX(I)
(0049)             IF (RANF(2).LT.P) GO TO 130
(0050)             GO TO 120
(0051)  C       .....LONG-LIVED MID SERAL SPECIES.  INCREASING MORTALITY.
(0052)       80    IF (DBH(K).GT.0.5*DBHMX(I)) GO TO 90
(0053)             P = 0.8866+0.1112/(0.5-1./DBHMX(I))*(DBH(K)-1.)/DBHMX(I)
(0054)             IF (RANF(2).LT.P) GO TO 130
(0055)             GO TO 120
(0056)       90    P = 1.0538-0.1112*DBH(K)/DBHMX(I)
(0057)             IF (RANF(2).LT.P) GO TO 130
(0058)             GO TO 120
(0059)  C       .....LATE SERAL SPECIES.
```

```
060)    100     IF (DBH(K).GT.0.1*DBHMX(I)) GO TO 110
061)            P = 0.9956+0.00335/(0.1-1./DBHMX(I))*(DBH(K)-1.)/DBHMX(I)
062)            IF (RANF(2).LT.P) GO TO 130
063)            GO TO 120
064)    110     P = 1.0053-0.0635*DBH(K)/DBHMX(I)
065)            IF (RANF(2).LT.P) GO TO 130
066)    120     CONTINUE
067)            NTREES(I) = NTREES(I)-1
068)  C       .....
069)  C       .....CHECK TO SEE IF DEAD TREE CAN STUMP SPROUT.  SET KSPRT = -1
070)  C       .....IF TREE CAN SPROUT
071)  C       .....
072)            IF (DBH(K).GT.SPRTMN(I).AND.DBH(K).LT.SPRTMX(I)) KSPRT(I) = -1
073)            IF (PMORT .NE. 9) GO TO 126
074)    125   FORMAT (3X,I3,F6.2,I4)
075)             WRITE (9,125) NCODE(K),DBH(K),KYR
076)    126     CONTINUE
077)            DBH(K) = -1.0
078)    130 CONTINUE
079)  C       .....
080)  C       .....REWRITE DIAMETERS AND AGES TO ELIMINATE DEAD TREES
081)  C       .....
082)    140 K = 0
083)        DO 150 I=1,NTOT
084)            IF (DBH(I).LT.0.) GO TO 150
085)            K = K+1
086)            DBH(K) = DBH(I)
087)            IAGE(K) = IAGE(I)
088)            NCODE(K) = NCODE(I)
089)    150 CONTINUE
090)        NTOT = K
091)    160 CONTINUE
092)         RETURN
093)         END
```

```
(0001)         SUBROUTINE OUTPUT (KYR, IPLOT)
(0002)         COMMON /FOREST/ NTREES(50), DBH(700), IAGE(1000), KSPRT(50), NEWTR(50)
(0003)        1, SUMLA(1000), NEW(50), NCODE(700), ISEL(50)
(0004)         COMMON /PARAM/ AAA(8, 100), DMAX(50), DMIN(50), B3(50), B2(50), ITOL(50)
(0005)        1, AGEMX(50), G(50), SPRTND(50), SPRTMN(50), SPRTMX(50), KTIME(50), A1(50)
(0006)        2, A2(50), BB(50), BC(50), C(50), WMIN(50), IREQ(50, 4), DBHMX(50), B1(50),
(0007)        3B4(50), HMAX(50), DRANGE(50)
(0008)         COMMON /PASSX/ A(501, 25), FB(50)
(0009)         COMMON /COUNT/ NTOT, NYEAR, IPERT, INT, IN, PMORT
(0010)         COMMON /CONST/ NSPEC, SOILQ, PMS, TQI, TQII, SD, IQEQG
(0011)         DIMENSION BAR(50)
(0012)          REAL LA
(0013)         KYR1 = KYR+1
(0014)         AREA = 0.0
(0015)         TBAR = 0.0
(0016)         TOBAR = 0.0
(0017)         DO 10 I=1, NSPEC
(0018)         FB(I) = 0.
(0019)         A(KYR1, I) = 0.
(0020)      10 BAR(I) = 0.
(0021)         A(KYR1, 22) = 0.
(0022)         A(KYR1, 23) = 0.
(0023)         A(KYR1, 24) = 0.
(0024)         A(KYR1, 25)=0.0
(0025)         IF (NTOT.EQ.0) GO TO 50
(0026)         DO 40 J=1, NTOT
(0027)            I = NCODE(J)
(0028)            IF (I.NE.6) GO TO 20
(0029)             HT=137.+B2(6)*DBH(J)-B3(6)*DBH(J)**2
(0030)            BAR(I) = BAR(I)+0.02+2.09*(HT/100.)*DBH(J)-0.0015*(HT/100.)*
(0031)        1   DBH(J)**2
(0032)            FBIO=3.2+1.89*ALOG(DBH(J))
(0033)            GO TO 30
(0034)      20    BAR(I) = BAR(I)+EXP(A1(I)+BB(I)*ALOG(DBH(J)))
(0035)               LA=(256.*ALOG(DBH(J))-639.)*2.5
(0036)            FBIO=EXP(A2(I)+BC(I)*ALOG(DBH(J)))
(0037)             IF(DBH(J).GE.50.) FBIO=LA*(1/C(16))*DRANGE(I)
(0038)      30    BAR(I) = BAR(I)+FBIO
(0039)            A(KYR1, 25)=A(KYR1, 25)+FBIO*.005
(0040)            FB(I)=FB(I)+FBIO*.005
(0041)          GO TO (32, 32, 32, 32, 34, 34, 34, 32, 32, 32, 32, 32, 32, 32, 32, 32, 34,
(0042)        1 32, 32, 32, 34), I
(0043)     32          AREA=AREA + FBIO*C(I)/2.5
(0044)                 GO TO 40
(0045)     34          AREA=AREA + FBIO*C(I)/2.0
(0046)      40 CONTINUE
(0047)      50 CONTINUE
(0048)         DO 60 I=1, NSPEC
(0049)      60 TBAR = TBAR+BAR(I)
(0050)         TBAR = TBAR*0.005
(0051)         DO 70 IV1=1, NSPEC
(0052)            A(KYR1, IV1) = A(KYR1, IV1)+BAR(IV1)*0.005
(0053)      70 CONTINUE
(0054)         ATOT = NTOT
(0055)         N1 = NSPEC+1
(0056)         N2 = N1+1
(0057)         N3 = N2+1
(0058)         A(KYR1, N1) = A(KYR1, N1)+TBAR
(0059)   C     TYR(KYR1) = TBAR
```

```
0001)         SUBROUTINE PLOTIN (IPLOT)
0002)         COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),KSPRT(50),NEWTR(50)
0003)        1,SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
0004)         COMMON /CONST/ NSPEC,SOILQ,PMS,TGI,TGII,SD,IGEOG
0005)         COMMON /COUNT/ NTOT,NYEAR,IPERT,INT,IN,PMORT
0006)  C      .....
0007)  C      .....INITIALIZE VARIABLES TO START SIMULATION ON BARE PLOT
0008)  C      .....NTREES CONTAINS NUMBER OF TREES FOR EACH SPECIES
0009)  C      .....DBH CONTAINS DIAMETER AT BREAST HEIGHT FOR EACH TREE
0010)  C      .....KSPRT IS USED TO FLAG THE TREES THAT CAN SPROUT
0011)  C      .....AREA CONTAINS THE LOCATION OF EACH TREE
0012)  C      .....NOGRO IS USED TO FLAG THE TREES THAT DON"T GROW
0013)  C      .....IAGE CONTAINS THE AGE FOR EACH TREE
0014)  C      .....
0015)         IPLOT = IPLOT+1
0016)         NTOT = IN
0017)         DO 10 I=1,NSPEC
0018)            IAGE(I) = 0
0019)            NTREES(I) = 0
0020)     10  CONTINUE
0021)         NSPE1 = NSPEC+1
0022)         DO 20 I=NSPE1,700
0023)            IAGE(I) = 0
0024)     20  CONTINUE
0025)  C       IF IN NOT EQUAL TO ZERO READ IN TREE SIZES AND SPECIES
0026)  C       DATA AT END OF DATA FILE SUCDAT
0027)  C
0028)          IF (IN .EQ. 0) GO TO 80
0029)  C
0030)  C       READ IN THE NUMBER OF TREES OF EACH SPECIES
0031)  C
0032)          READ (5,25) (NTREES(I),I=1,NSPEC)
0033)    25    FORMAT (21I3)
0034)              READ (5,30) (NCODE(K),DBH(K),K=1,IN)
0035)     30       FORMAT (7(I3,1X,F6.2,7X))
0036)     40       CONTINUE
0037)     50   CONTINUE
0038)          WRITE (6,60) NTOT
0039)    60    FORMAT (8H NTOT = , I5)
0040)         WRITE (6,70) (NCODE(K),DBH(K), K=1,IN)
0041)    70       FORMAT (1X,7(I5,F6.2))
0042)    80       CONTINUE
0043)         RETURN
0044)         END
```

```
(0001)         SUBROUTINE PLTREE (KYR,IPLOT)
(0002)         COMMON /PARAM/ AAA(8,100)
(0003)         COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),KSPRT(50),NEWTR(50)
(0004)        1,SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
(0005)         COMMON /CONST/ NSPEC,SOILQ,PMS,TQI,TQII,SD,IGEOG
(0006)         COMMON /COUNT/ NTOT,NYEAR,IPERT,INT,IN,PMORT
(0007)         COMMON /PASSX/ A(501,25),FB(50)
(0008)         DIMENSION D(25,20)
(0009)         DATA PI/0.314159265E01/
(0010)         KYR1 = KYR+1
(0011)         BAREA=0.
(0012)         DO 5 K=1,NTOT
(0013)            BAREA=BAREA+PI*(DBH(K)/2.)**2
(0014)       5    CONTINUE
(0015)         BAREA=(BAREA * 5.)/10000.
(0016)   C
(0017)   C      PRINT OUT TABLE FOR LAST YEAR
(0018)   C
(0019)         IF (NYEAR.EQ.KYR) GO TO 9
(0020)   C
(0021)   C      WRITE ONTO TAPE8 STAND INFORMATION TO BE USED IN APLOT:
(0022)   C        YEAR, STAND BIOMASS, LEAF AREA, STAND BASAL AREA, &
(0023)   C        BIOMASS FOR ABIES AMABILIS, PSEUDOTSUGA MENZIESII & TSUGA
(0024)   C        HETEOPHYLLA
(0025)   C        RECORDED FOR EVERY OTHER YEAR ONTO TAPE8
(0026)   C
(0027)           IF (MOD(KYR,2) .NE. 0) GO TO 100
(0028)          WRITE (8,8) KYR,A(KYR1,22),A(KYR1,24),BAREA,
(0029)        1      A(KYR,1),A(KYR,16),A(KYR,19)
(0030)     8    FORMAT (7(E10.3,2X))
(0031)   C
(0032)   C       ONLY WRITE OUT TABLE EVERY 50 YEARS
(0033)   C       OR FOR FIRST 5 YEARS
(0034)           IF (KYR.LE.5) GO TO 9
(0035)            IF (MOD(KYR,50) .NE. 0) GO TO 100
(0036)   C
(0037)     9   WRITE (6,10) KYR,IPLOT,TQI,PMS
(0038)      10 FORMAT (1H1,4HYEAR,I6,2X,11HPLOT NUMBER,I6,4X,6HTQI = ,F6.1,4X,
(0039)        16HPMS = ,F6.1,4X,18HGEOGRAPHIC REGION:)
(0040)           GO TO (12,14,16,18),IGEOG
(0041)      12 WRITE (6,13)
(0042)      13 FORMAT (1H+,T86,22H SOUTH OF SANTIAM PASS)
(0043)           GO TO 20
(0044)      14 WRITE (6,15)
(0045)      15  FORMAT (1H+,T86,28H SANTIAM PASS TO MT. RAINIER)
(0046)           GO TO 20
(0047)      16 WRITE (6,17)
(0048)      17  FORMAT (1H+,T86, 22H MT. RAINIER TO CANADA)
(0049)           GO TO 20
(0050)      18 WRITE (6,19)
(0051)      19  FORMAT (1H+,T86, 18H OLYMPIC PENINSULA)
(0052)           BIOM = A(KYR1,22)
(0053)      20 WRITE (6,22) A(KYR1,22),A(KYR1,23),A(KYR1,24)
(0054)      22 FORMAT (1H+,45H TOTAL FOLIAGE BIOMASS PLUS STEM WOOD BIOMASS
(0055)        129H (W/O BARK) TONS PER HECTARE=,F10.5,
(0056)        2/2X,38H TOTAL NUMBER OF TREES PER 1/5 H PLOT=,F6.1,6X,4HLEAF
(0057)        312H AREA INDEX=,F10.5)
(0058)           WRITE (6,27) BAREA, A(KYR1,25)
(0059)      27 FORMAT (1HO,18H THE BASAL AREA IS,F10.2,14H SQ. M/HECTARE,6X,
```

```
      145H TOTAL FOLIAGE BIOMASS (INCLUDES PETIOLES) IS,F8.3//)
C
C       CALCULATE THE NUMBER OF TREES IN EACH DIAMETER CLASS (FOR
C        EVERY 10 CM).  FIRST INITIALIZE D(I,J) TO ZERO.
C
       DO 31 I=1,NSPEC
          DO 31 J=1,20
             D(I,J)=0.0
   31     CONTINUE
        KTOT=A(KYR1,23)
       DO 46 K=1,NTOT
            I=NCODE(K)
            DC=DBH(K)/10.
            IF (DC .GT. 20.) WRITE (6,35) DC
   35       FORMAT (5H DC= ,F8.2)
            IDC=IFIX(DC)
            IF(IDC .GE. 16) IDC=16
            D(I,IDC)=D(I,IDC) +1.
    46      CONTINUE
       WRITE (6,47)
    47 FORMAT (1H ,6X,7HSPECIES,13X,7H NUMBER,2X,6H ABOVE,1X,
      +8H FOLIAGE,
      120X,26H NUMBER PER DIAMETER CLASS/24X,9H OF TREES,1X,
      27H GROUND,2X,
      38H BIOMASS,1X,40H  10  20  30  40  50  60  70  80  90 100
      48H 110 120
      517H 130 140 150 160+/34X,8H BIOMASS
      611X,35H-20 -30 -40 -50 -60 -70 -80 -90-100
      725H-110-120-130-140-150-160 )
       DO 49 I=1,NSPEC
          WRITE (6,48) I,(AAA(J,I),J=1,5),NTREES(I),A(KYR,I),FB(I),
      1(D(I,J),J=1,16)
    48    FORMAT (1H ,I2,1X,5A4 ,2X,I6,2X,F6.2,2X,F6.2,4X,16(F4.0))
    49    CONTINUE
       WRITE (6,50)
    50 FORMAT ( ///)
C   60 WRITE (6,65)
    65 FORMAT (1HO,41HSPECIES CODES, DIAMETERS, AND AGES FOLLOW)
C      WRITE (6,70) (NCODE(K),DBH(K),IAGE(K),K=1,NTOT)
    70 FORMAT (1HO,7(I3,1X,F6.2,1X,I4,2H--)/(1HO,7(I3,1X,F6.2,1X,I4,2H--)
      1))
  100   CONTINUE
C
C      FOR PMORT=7, PRINT OUT STAND STRUCTURE AT TIME 700 FOR INPUT TO
C         NEXT RUN OF CLIMACS
C
         IF (PMORT .NE. 7) GO TO 120
          IF (KYR .NE. 700) GO TO 120
         WRITE (9, 110) (NCODE(K),DBH(K),K=1,NTOT)
   110   FORMAT (7(I3,1X,F6.2,7X))
   120   CONTINUE
C
       RETURN
       END
```

```
(0001)          FUNCTION RANDOM (NSEED)
(0002)          COMMON /SEED/ USEED(13)
(0003)          INTEGER USEED
(0004)          ISEED = USEED(NSEED)*100.
(0005)          DUM = RND(ISEED)
(0006)          RANDOM = RND(0)
(0007)          RETURN
(0008)          END
```

```
(0001)          SUBROUTINE RANSEE
(0002)          COMMON /SEED/ USEED(13)
(0003)          INTEGER USEED
(0004)
(0005)          DUM = RND(1)
(0006)
(0007)          DO 10 I = 1,13
(0008)       10 USEED(I) = RND(0)
(0009)
(0010)          RETURN
(0011)          END
```

```
(0001)          REAL*4 FUNCTION RANF( IDUM )
(0002)
(0003)    C     UNIFORM RANDOM NUMBER GENERATOR
(0004)
(0005)          RANF = RND(0)
(0006)
(0007)          RETURN
(0008)          END
```

```
(0001)          SUBROUTINE SELECT
(0002)          COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),KSPRT(50),NEWTR(50)
(0003)         1,SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
(0004)          COMMON /PARAM/ AAA(8,100),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
(0005)         1,AGEMX(50),G(50),SPRTND(50),SPRTMN(50),SPRTMX(50),KTIME(50),A1(50)
(0006)         2,A2(50),BB(50),BC(50),C(50),WMIN(50),IREG(50,4),DBHMX(50),B1(50),
(0007)         3B4(50),HMAX(50),DRANGE(50)
(0008)          COMMON /CONST/ NSPEC,SOILG,PMS,TGI,TGII,SD,IGEOG
(0009)          DO 10 I=1,NSPEC
(0010)             ISEL(I) = 0
(0011)    C     .....CHECK MAXIMUM WATER STRESS.
(0012)             IF (WMIN(I).LT.PMS) GO TO 10
(0013)    C     .....CHECK TEMPERATURE REQUIREMENTS.
(0014)             IF (TGI.LT.DMIN(I).OR.TGI.GT.DMAX(I)) GO TO 10
(0015)    C     .....CHECK SPECIES DISTRIBUTIONS.
(0016)    C     .....REGION 1 = SOUTH OF SANTIAM PASS.
(0017)    C     .....REGION 2 = SANTIAM PASS TO MT. RAINIER NP.
(0018)    C     .....REGION 3 = MT. RAINIER NP TO CANADIAN BOARDER.
(0019)    C     .....REGION 4 = OLYMPIC NP.
(0020)             IF (IREG(I,IGEOG).NE.1) GO TO 10
(0021)             ISEL(I) = 1
(0022)       10 CONTINUE
(0023)          RETURN
(0024)          END
```

```
001)          SUBROUTINE SPROUT
002)         COMMON /FOREST/ NTREES(50),DBH(700),IAGE(1000),KSPRT(50),NEWTR(50)
003)        1,SUMLA(1000),NEW(50),NCODE(700),ISEL(50)
004)         COMMON /PARAM/ AAA(8,100),DMAX(50),DMIN(50),B3(50),B2(50),ITOL(50)
005)        1,AGEMX(50),G(50),SPRTND(50),SPRTMN(50),SPRTMX(50),KTIME(50),A1(50)
006)        2,A2(50),BB(50),BC(50),C(50),WMIN(50),IREQ(50,4),DBHMX(50),B1(50),
007)        3B4(50),HMAX(50),DRANGE(50)
008)          COMMON /CONST/ NSPEC,SOILG,PMS,TGI,TGII,SD,IGEOG
009)          COMMON /DEAD/ NOGRO(700)
010)          COMMON /COUNT/ NTOT,NYEAR,IPERT,INT,IN,PMORT
011)          COMMON /SEED/ USEED(13)
012)          INTEGER USEED
013)    C     .....
014)    C     .....SMALLEST AVERAGE STUMP SPROUT IS .1 CM
015)    C     .....
016)          SIZE = .1
017)    C     .....
018)    C     .....SUM TOTAL NUMBER OF TREES
019)    C     .....
020)    C     .....DETERMINE WHICH SPECIES CAN SPROUT
021)    C     .....
022)           NW = 0
023)          DO 10 I=1,NSPEC
024)             IF (SPRTND(I).LE.0.) GO TO 10
025)             IF (KSPRT(I).GE.0) GO TO 10
026)             NW = NW+1
027)             NEW(NW) = I
028)       10 CONTINUE
029)    C     .....
030)    C     .....CHECK FOR SPROUTS
031)    C     .....
032)          IF (NW.EQ.0) GO TO 30
033)    C     .....
034)    C     .....CHOOSE RANDOM NUMBER OF SPROUTS
035)    C     .....
036)          NW = NW*RANF(3)+1.0
037)    C     .....
038)    C     .....SELECT SPECIES TO SPROUT
039)    C     .....
040)          NSPC = NEW(NW)
041)    C     .....
042)    C     .....SPRTND IS THE TENDENCY FOR THE ITH SPECIES TO STUMP OR
043)    C     .....ROOT SPROUT.  THE VALUE OF SPRTND IS THE AVERAGE NUMBER
044)    C     .....OF SPROUTS THAT MIGHT OCCUR WITH A TREE DEATH
045)    C     .....
046)    C     .....
047)    C     .....RANDOMLY SELECT NUMBER OF TREES TO SPROUT
048)    C     .....
049)          NSPRT = RANF(4)*SPRTND(NSPC)+1
050)          DO 20 I=1,NSPRT
051)             NTREES(NSPC) = NTREES(NSPC)+1
052)             NTOT = NTOT+1
053)             IF (NTOT.GT.700) CALL ERR
054)             IAGE(NTOT) = 0
055)             NCODE(NTOT) = NSPC
056)             DBH(NTOT) = SIZE+.1*(1.0-RANF(5))**3
057)    C     .....
058)    C     .....STORE DIAMETERS AND AGES FOR NEW SPROUTS
059)    C     .....
```

Appendix 2

Tabular Output of Program CLIMACS

Year 400 Plot Number 1 TGI = 76.0 PMS = 13.0 Geographic region: Olympic Peninsula
Total foliage biomass plus stemwood biomass (without bark) tons per hectare = 499.77795
Total number of trees per 1/5-ha plot = 359.0 Leaf area index = 6.94256
Basal area is 61.25 m^2/ha Total foliage biomass (includes petioles) is 9.454

Species	Number of trees	Above-ground biomass	Foliage biomass	Number per diameter class															
				10 -20	20 -30	30 -40	40 -50	50 -60	60 -70	70 -80	80 -90	90 -100	100 -110	110 -120	120 -130	130 -140	140 -150	150 -160	160+
Abies amabilis	243	27.16	3.13	205	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Abies grandis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Abies lasiocarpa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Abies procera	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Acer macrophyllum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Alnus rubra	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Arbutus menziesii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Castanopsis chrysophylla	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chamaecyparis nootkatensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Libocedrus decurrens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Picea engelmannii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Picea sitchensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pinus contorta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pinus lambertiana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pinus monticola	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pinus ponderosa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pseudotsuga menziesii	2	411.99	1.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Quercus garryana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thuja plicata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tsuga heterophylla	293	60.66	5.31	105	45	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Tsuga mertensiana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Dale, Virginia H.; Hemstrom, Miles. CLIMACS: A computer model of forest stand development for western Oregon and Washington. Res. Pap. PNW-327. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, **1984.** 60 p.

A simulation model for the development of timber stands in the Pacific Northwest is described The model grows individual trees of 21 species in a 0.20-hectare (0.08-acre) forest gap. The model provides a means of assimilating existing information, indicates where knowledge is deficient, suggests where the forest system is most sensitive, and provides a first testing ground for hypotheses. Model verification simulations are included for up to 500 years on various sites Fire, wind, or clearcutting can occur at intervals and intensities specified by users. The model was developed by modifying an existing forest succession simulator of eastern deciduous forests. Birth, growth, and death of individual trees are functions of existing light and temperature conditions, competition and species characteristics. Modifications of the existing simulator include tree height growth being related to temperature and moisture conditions, the foliage biomass to diameter relationship being more realistic, and five mortality classes and shade tolerance classes being defined.

Keywords: Succession, models, simulation, community dynamics (plant).

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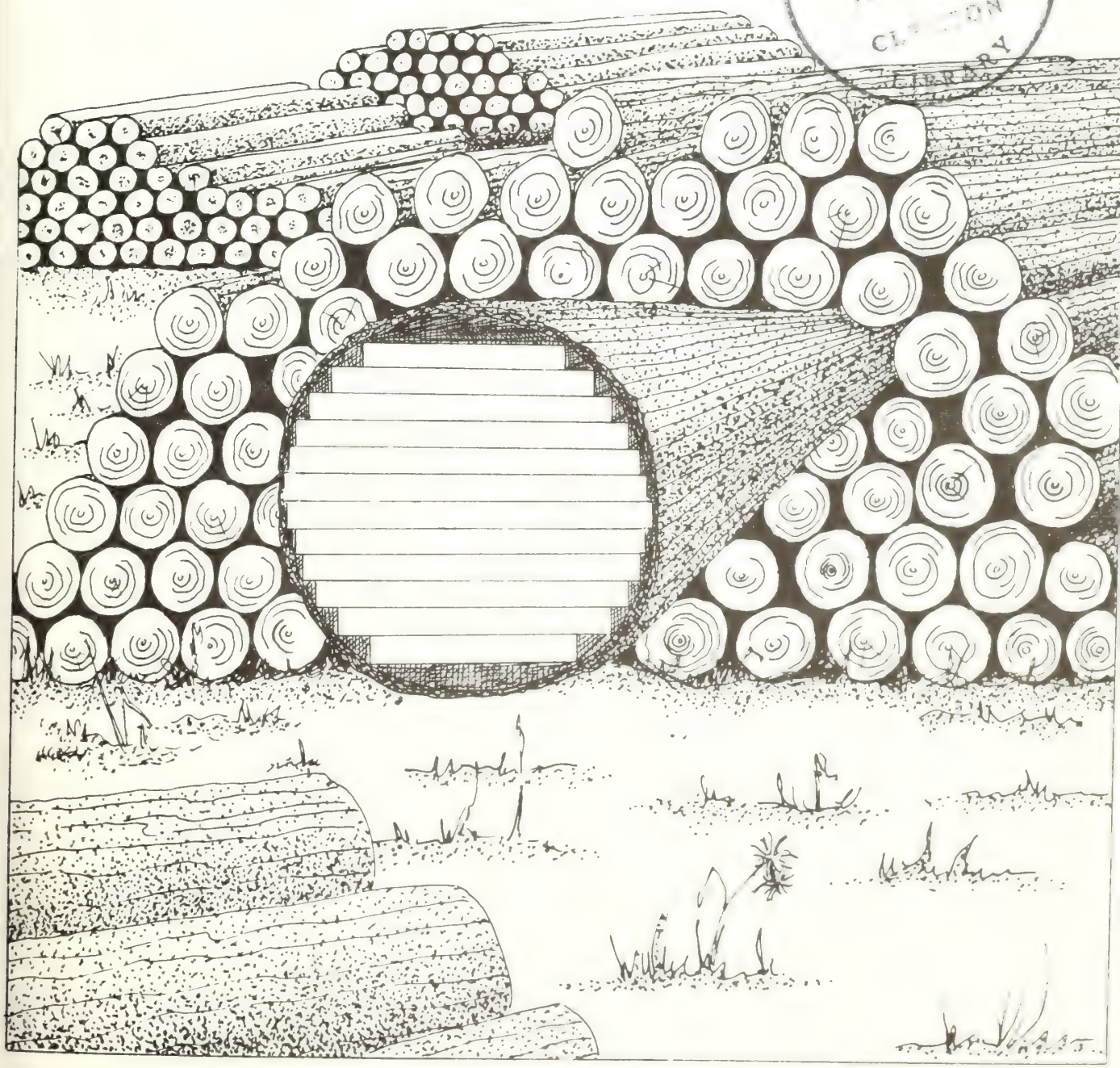
Pacific Northwest
Forest and Range
Experiment Station

Research Paper
PNW-328

January 1985

Lumber Recovery From Ponderosa Pine in the Black Hills, South Dakota

Marlin E. Plank



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Abstract

Plank, Marlin E. Lumber recovery from ponderosa pine in the Black Hills, South Dakota. Res. Pap. PNW-328. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. **1985.** 14 p.

A sample of 400 ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) trees was selected from each of two sale areas in the Black Hills National Forest, South Dakota. The logs were processed through two sawmills into 1-inch-thick boards. Estimates of volume and value recovery based on cubic volume and board foot volume are shown in tables and figures.

Keywords: Lumber recovery, lumber yield, ponderosa pine (Black Hills), *Pinus ponderosa*, South Dakota (Black Hills).

Summary

A sample of 400 ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) trees was selected from two sale areas in the Black Hills National Forest, South Dakota. The logs were processed through two sawmills and the primary product was 1-inch boards. Although there were slight differences between the two mills for some response variables, the data were combined so that overall product recovery information could be presented for ponderosa pine in the Black Hills. Recovery estimates are shown in tables and figures for both Scribner log volume and cubic log volume. Analysis of the data for mill-length logs indicated that recovery percent (overrun) would range from 151 percent for 5-inch logs to 108 percent for 19-inch logs. Cubic volume recovery of rough-green lumber increased from 41 percent to 55 percent over that same range of diameters. Over half the lumber volume recovered was graded No. 3 Common. A section on application of study results is included.

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Introduction

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is the predominant tree species on 1.3 million acres in the Black Hills of South Dakota. Sawtimber volume, which includes trees 9 inches in diameter at breast height (d.b.h.) and larger, totals about 4,483 million board feet. Because production of lumber is a major industry and contributes to the local economy, it is vital that the wood-using industries remain competitive with those producing alternative products. Full and efficient use of the resource is required to maintain this competitiveness, and to do so requires current information about the volumes and grades of lumber that can be produced.

The major objective of this study was to determine the lumber volume, value, and grade recovered from ponderosa pine sawtimber in the Black Hills. This research provides a basis for estimating the volume and grade recovery from similar logs. The information is useful to loggers, sawmill operators, lumber remanufacturers, timber growers, and forest administrators. It can be used for making log allocations and in improving mill design and processing decisions.

Methods

Sample Selection

About 200 trees were selected from each of two sale areas in the Black Hills National Forest. The two areas contained trees that were typical of those found in many areas within the Forest. All trees from one area went to one sawmill in eastern Wyoming (mill A); trees from the other area went to a sawmill in western South Dakota (mill B). Trees were selected by 2-inch diameter classes and an attempt was made to sample about the same number of trees in each class (table 1). D.b.h. of the trees ranged from 5 to 23 inches in each of the samples and there were at least nine trees in each 1-inch diameter class from 6 through 16 inches.

Tree quality in the Black Hills is considered to be consistent and low, thus logs are generally not graded. Trees in the southern portion of the National Forest may be of lower overall quality than are those in the north. The lack of convincing evidence of the difference in quality and practical considerations regarding harvesting limited sampling to the two sale areas in the north. No attempt was made to sample old growth and young growth separately; trees were selected exclusively by diameter.

Table 1—Number of ponderosa pine trees selected from two sample areas in the Black Hills

	Number of trees	
D.b.h class	Area 1 (mill A)	Area 2 (mill B)
5- 6	18	18
7- 8	36	42
9-10	34	36
11-12	31	37
13-14	26	26
15-16	22	27
17-18	15	4
19-20	9	4
21-22	5	2
23	4	2

Harvesting and Log Identification

Trees were felled and bucked in accordance with normal industry practice. In the Black Hills, it is common practice to haul logs on "self-loading" trucks, so those logs are often bucked into 16-foot or shorter lengths. Trees for mill B were bucked into short logs while logs for mill A ranged from 32 to 56 feet. Total length of each tree and length and diameter of each bucked log were recorded. Each log was identified by tree number and position of the log within the tree. This number was used to identify lumber items produced from specific logs.

Scaling

After the logs were delivered to the respective millyards, they were rolled out and scaled. Scribner scale was taken by USDA Forest Service check scalers according to National Forest Log Scaling Handbook rules (USDA Forest Service 1973). Cubic scale was taken in conformance with the draft cubic log scaling handbook.[1/] The amount and reasons for each scale deduction were documented. Because logs delivered to mill B were already in milling lengths, no scale was taken on the log deck. Logs for mill A were bucked into milling lengths just prior to sawing and were scaled for Scribner volumes on the log deck. Average defect for Scribner volume in this sample was about 9 percent; sweep was the most common defect.

Lumber Manufacturing

Each mill was equipped with a circular head saw, a gang saw, edger, and a gang trimmer. In addition, mill A had a two-saw scragg fed by an end-dogging carriage and also had another small edger.

Logs were sawn to recover the usual lumber items produced by each mill. As logs entered the mill they were numbered sequentially. All the boards from a log were given the same number so that the recovery could be related back to the original log and tree. Only 1-inch boards were sawn with nearly all of the resulting lumber (97 percent) being in the Common grades.

All lumber was kiln-dried, planed, and graded. Grading was done by company graders under the supervision of a quality inspector from the Western Wood Products Association according to their grading rules (Western Wood Products Association 1977). Lumber was tallied in the surfaced dry condition, ready for shipment. Width of lumber ranged from 4 to 12 inches.

Analysis

The objective of this paper is to present overall product recovery information for ponderosa pine in the Black Hills. Analysis was therefore directed to (1) finding a suitable model for predicting lumber volume and value recovery, and (2) determining if lumber volume recovery was different for the two sample areas.

[1/] Review draft (1978) of the cubic scaling handbook available from USDA Forest Service, Timber Management, P.O. Box 2417, Washington, D.C. 20013.

Dependent variables for volume recovery include cubic recovery percent (CR%), lumber recovery factor (LRF), and recovery percent (overrun).[2] For value, the variables include dollars per thousand board feet lumber tally ($/MLT) and dollars per hundred cubic feet ($/CCF) of log scale. Experience indicates that the relationship of product recovery to log diameter is best described by polynomial equations using diameter (D) and combinations of D^2, $1/D$, and $1/D^2$ as independent variables. Models tested were:

$$y = b_0 + b_1 D,$$
$$y = b_0 + b_1 D^2,$$
$$y = b_0 + b_1 D + b_2 D^2,$$
$$y = b_0 + b_1 1/D,$$
$$y = b_0 + b_1 1/D + b_2 1/D^2, \text{ and}$$
$$y = b_0 + b_1 D + b_2 1/D + b_3 1/D^2.$$

Coefficient of determination and F value were the major criteria for selecting the best models. Statistical tests were made at ($P \leq 0.05$). Models selected for the appropriate dependent variable and the descriptive statistics are shown in the respective results section.

Differences in lumber recovery between the two areas were tested using CR% of rough-green lumber from mill-length logs. Cubic recovery percent of rough-green lumber, unlike overrun and LRF, reflects the actual volume of lumber recovered and is independent of lumber items sawn and the target sizes of each mill (Fahey and Snellgrove 1982). Covariance analysis was used to compare this recovery from the two mills. Although tests for a difference in slope or elevation between areas may have been significant, they were so low as not to be practically important when the y_m (Draper and Smith 1981) criterion was applied. Because of this, *lumber volume recovery was combined for the two areas.*

Results and Discussion

Volume and value recovery relationships discussed in this section are for mill-length logs only. Relationships discussed under the sections regarding direct product estimates are for log lengths as delivered to the mill. In that section, separate relationships are shown depending on whether the logs were woods length or mill length.

[2] Terms are defined in the glossary.

Cubic Recovery Percent

Cubic recovery percent can be based on rough-green or surfaced-dry lumber. Both are related to diameter and are shown in table 2 and figure 1. The difference between the recovery of green and dry lumber is the volume lost because of shrinkage and planer shavings. The percentages of lumber, planer shavings, and sawdust increase slightly with increasing log diameter, while the percentage available for chips decreases. These recovery percents are based on the gross cubic foot (CF) volume of logs.

Table 2—Estimated percent of cubic volume for products manufactured from ponderosa pine logs in the Black Hills

Scaling diameter	Lumber recovery factor	Rough-green lumber	Surfaced dry lumber	Shrinkage and planer shaving	Sawdust	Chippable volume
Inches	BF/CF	- - - - - - - - - - - - - -		Percent	- - - - - - - - - - - - - -	
5	4.6	41	25	16	9	50
6	4.6	41	25	16	9	50
7	4.7	43	26	17	9	48
8	4.9	44	28	16	9	47
9	5.1	46	29	17	10	44
10	5.3	47	30	17	10	43
11	5.5	49	31	18	10	41
12	5.6	50	32	18	10	40
13	5.8	51	33	18	10	39
14	5.9	52	34	18	10	38
15	6.0	53	35	18	11	36
16	6.1	53	35	18	11	36
17	6.2	54	36	18	11	35
18	6.3	55	37	18	11	34
19	6.4	55	37	18	11	34

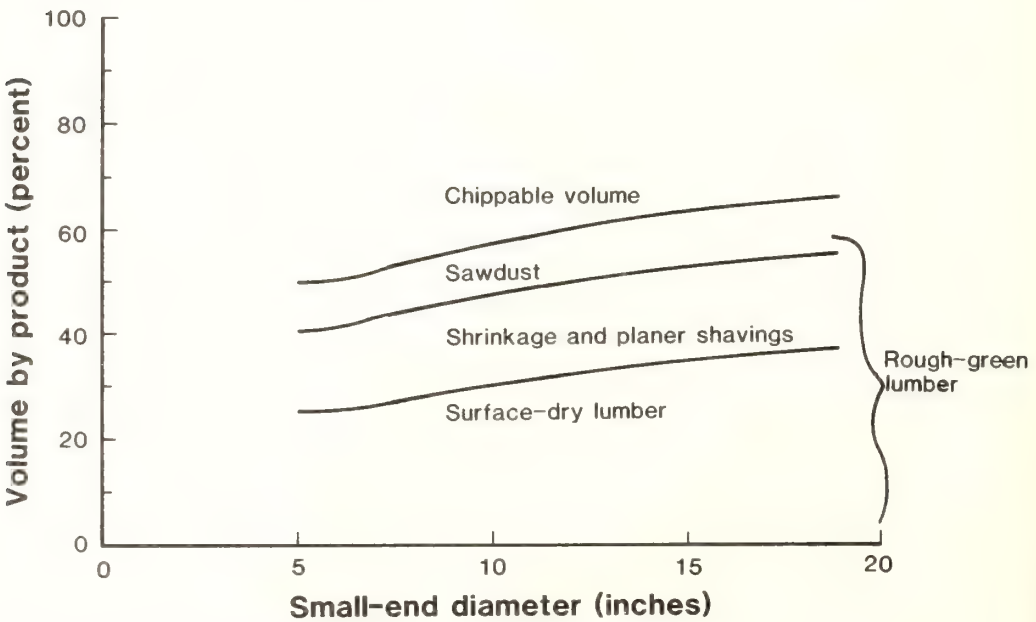

Figure 1.—Volume of products recovered expressed as a percentage of gross cubic foot volume of logs by diameter. This represents the combined recovery of mill-length logs from two sawmills cutting 1-inch-thick lumber.

Lumber Recovery Factor

The relationship between LRF and log diameter for data from both mills is shown in figure 2 and table 2. The trend is similar to that of CR% where there is a slight increase with increasing log diameter. Lumber recovery factor was 4.6 BF of lumber per CF of gross log volume for 5-inch diameter logs and gradually increased to 6.4 for 19-inch logs.

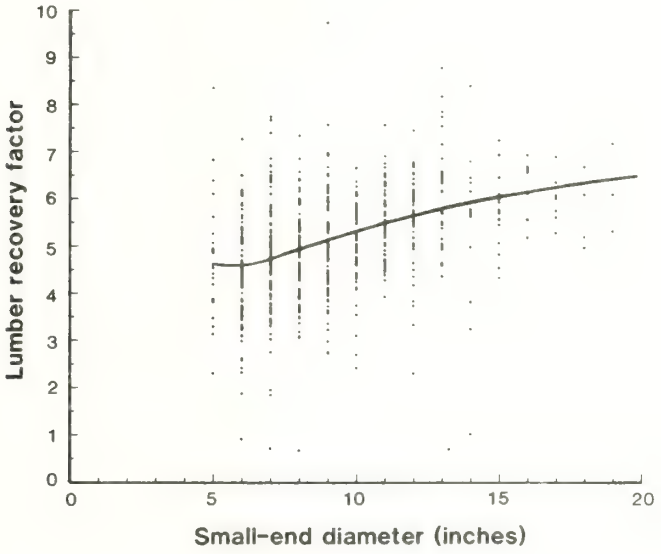

Figure 2.—Lumber recovery factor by scaling diameter for combined data from two sawmills. The recovery factor is for mill-length logs and is based on gross cubic foot volume of logs:

$$y = 8.25 - 40.89(1/d) + 113.57(1/d^2) .$$

Coefficient of determination = 0.160 and standard deviation from regression = 1.05.

Recovery Percent (Overrun)

Overrun is the common term used to describe the amount of lumber recovered that is in excess of the net log scale and is expressed as a percentage of the log scale. Recovery percent is often confused with overrun, but it is lumber tally divided by net log scale. A recovery percent of 150 would be equal to 50 percent overrun. Recovery percent is the term used in this report:

$$\text{Recovery percent} = \frac{\text{lumber tally}}{\text{net log scale}} \times 100 .$$

The relationship of recovery percent to diameter (based on Scribner board foot scale) is shown in table 3 and figure 3. The trend shows a steep decline from 151 percent at 5 inches to 117 percent at 12 inches, and falls gradually to 108 percent at 19 inches. This overall reduction of recovery percent with increasing log diameter is typical of mills that produce nominal 1-inch lumber. The statistical relationships between recovery percent and log diameter, although not strong, are significant. Estimates of recovery percent should be made by diameter class rather than by use of an average. Note that this study was not designed to replicate the same proportions of log diameters encountered in actual practice.

Table 3—Estimated recovery percent (overrun) from ponderosa pine logs in the Black Hills

Scaling diameter	Number of logs	Net scale	Defect	Estimated recovery (overrun)
Inches		Board feet	- - - - Percent	- - - -
5	19	205	0	151
6	109	1475	14	142
7	125	2910	11	135
8	102	2460	10	130
9	93	3170	8	126
10	66	3080	10	122
11	66	3980	8	120
12	46	3310	6	117
13	33	2940	7	116
14	16	1520	16	114
15	16	2090	3	113
16	8	1130	8	111
17	5	800	9	110
18	6	1080	14	109
19	4	890	10	108

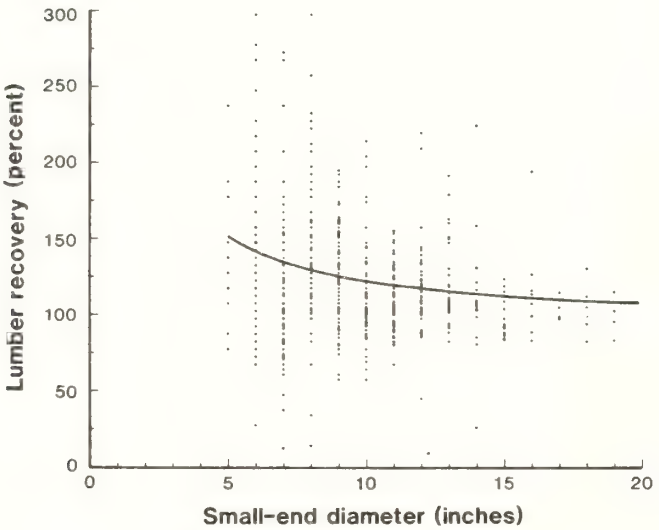

Figure 3.—Percent of lumber recovery (overrun) over scaling diameter. Data are combined recovery for mill-length logs from two sawmills cutting 1-inch-thick lumber:

$$y = 93.12 + 291.61(1/d) .$$

Coefficient of determination = 0.052 and standard deviation from regression = 42.0.

Table 4—Estimated percent of volume in various lumber grades, by diameter class, for ponderosa pine logs in the Black Hills

	Lumber grade				
Diameter	Molding and Selects	2 and BTR Common	3 Common	4 Common	5 Common
Inches	- - - - - - - - - - - - - -		Percent	- - - - - - - - - - - - - -	
5		12	49	22	17
6	1	19	54	18	8
7	1	19	59	17	4
8	1	19	59	18	3
9	2	14	62	19	2
10	3	10	64	21	2
11	3	8	65	22	2
12	4	6	64	23	3
13	5	5	62	24	4
14	5	4	59	27	5
15	6	4	55	29	6
16	7	4	53	30	6
17	7	4	51	32	6
18	8	3	47	37	5
19	6	3	40	48	3

umber Grade

Most sawmills in the Black Hills that cut 1-inch boards produce a high proportion of Common grades of lumber; this study was no different. The greatest proportion of volume was in No. 3 Common with lesser amounts in the other Common grades. Mill A produced about 5 percent of the volume in Moulding and Selects; mill B obtained only slightly more than 1 percent in Selects and did not cut Moulding. Table 4 shows the estimated recovery percent of each lumber grade, by 1-inch diameter class, for both mills combined.

Approximate percentage of total volume recovered for various lumber grades in earlier studies (Landt and Woodfin 1959, Mueller and Kovner 1967) is shown in table 5. There was little difference in average recovery of No. 4 and No. 5 Common among all studies. The current study produced a higher proportion of No. 3 Common over the same range of diameters than did previous studies. One study had an average log diameter of about 11 inches; the average for the current study was about 9 inches. On the average, logs from the previous studies came from larger trees and this is probably the reason for the higher quality of lumber in those studies.

Table 5—Percent of total volume recovered, by lumber grade, for two previous ponderosa pine studies in the Black Hills

Grade	Average volume recovered (percent)	
	1959 study[1/]	1967 study[2/]
Shop and Better	10	15
2 and BTR Common	21	25
3 Common	35	33
4 Common	29	25
5 Common	5	2

[1/] Landt and Woodfin 1959.

[2/] Mueller and Kovner 1967.

Table 6—1978 lumber prices for White Woods[1/] in the Black Hills

Item	Lumber grade						
	C & BTR Select	D Select	Moulding	2 & BTR Common	3 Common	4 Common	5 Common
	Dollars/MLT						
1 x 4	732	495	444	330	168	126	97
1 x 6	888	602	444	333	200	143	97
1 x 8	824	576	444	316	202	156	97
1 x 10	894	592	444	288	201	179	97
1 x 12	1047	834	444	344	243	188	97

[1/] White Woods are Engelmann spruce, any true firs, any hemlocks, and any pines.

Value

Lumber.—Lumber value is determined by applying an appropriate price to the volume by grades for various items of lumber produced from a log. Prices used in this study are shown in table 6. The total value of the lumber items divided by the total volume of those items ($/MLT) is a useful indication of log quality. The relationship of $/MLT to log diameter is shown in figure 4. There is only a slight increase in value with increasing diameter because the quality of lumber recovered from this resource did not change greatly over the limited range of diameters. There was a large amount of variation around the mean of each diameter that could not be explained by the model. The relationship is significant but practicality should dictate whether to use lumber values based on diameter rather than an average.

Log.—Dollars per hundred cubic feet of log volume ($/CCF) is the value of lumber from a log divided by the cubic volume of that log. It expresses the combination of average value of the lumber ($/MLT) and the percentage of cubic volume recovered. The relationship of $/CCF to diameter is shown in figure 5 for all data combined. As expected, the value increased with increasing diameter because CR% and $/MLT both increased with diameter.

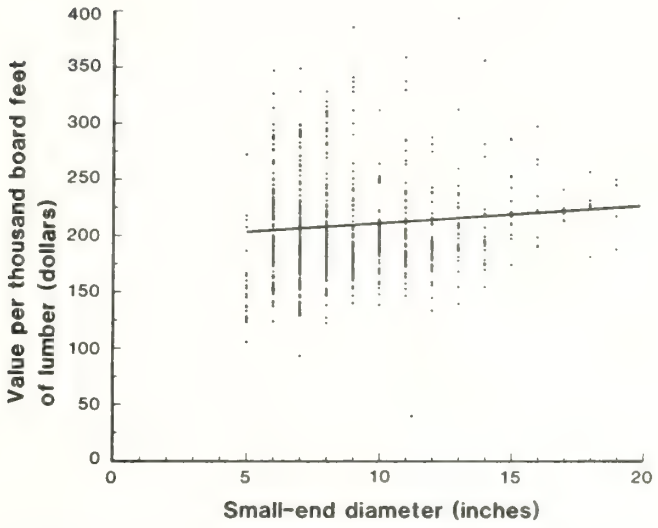

Figure 4.—Dollars per thousand board feet ($/MLT) of lumber tally, by scaling diameter, for both mills. This curve follows the general trend expected—value increasing with diameter. The limited size of the trees in the Black Hills, however, precludes the high value often obtained from ponderosa pine in areas where larger trees are prevalent:

$$y = 195.46 + 1.61(d) .$$

Coefficient of determination = 0.010 and standard deviation from regression = 45.78.

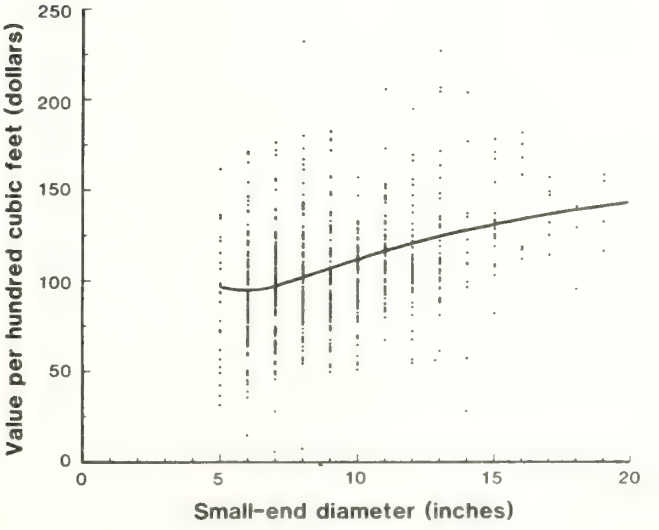

Figure 5.—Dollars per hundred cubic feet ($/CCF), by scaling diameter, for data combined from both mills. Cubic recovery percent and the average value of the lumber both increased with diameter; consequently, the $/CCF follows the same trend:

$$y = 193.03 - 1144.49(1/d) + 3325.14(1/d^2) .$$

Coefficient of determination = 0.125 and standard deviation from regression = 30.93.

Estimating Products

Volume and value of products can be predicted directly from cubic log scale. Cubic scale provides a less variable and more accurate estimate of volume than Scribner scale (Fahey and others 1981); it is, therefore, a better predictor of products. The relationships of product volume to scale volume in this section are compared for the two mills and are based on cubic product scale.[3/] The logs were scaled in the lengths delivered to the mills. Logs for mill A were scaled in the long log or tree length form and those for mill B were scaled as mill-length logs. The relationship of total lumber tally, chippable material, and sawdust to log volume is shown in figure 6. Figure 7 shows the relationship for value. There is a strong correlation between both volume and value of products and cubic log volume as evidenced by the R^2 statistic on each figure.

Comparison of Mill A and Mill B

The primary objective of this paper is to determine the overall volume and lumber grade recovery from ponderosa pine in the Black Hills, but it became apparent during the analysis that there were some differences in the recovery data obtained at each mill. The objective of this section is to examine the differences in volume recovery between the two mills and explain why these differences occurred.

Although the equipment in the two mills was similar, the conversion efficiency and lumber items produced were different (table 7). Actual thickness of nominal 1-inch rough-green lumber at mill A was 32/32-inch and at mill B it was 35/32-inch, therefore, mill A would be expected to attain a higher recovery of volume. Evidence of this would be reflected predominantly in LRF and overrun. Cubic recovery based on rough-green lumber dimensions does not vary significantly for any mill that produces similar items with similar equipment.

The average LRF was 5.3 for mill A and 5.0 for mill B. Because mill B cut thicker green sizes, it lost more to planer shavings than did mill A. For each 1,000 CF of log volume, mill A recovered an average of 5,300 BF of surfaced dry lumber but mill B only recovered 5,000 BF. Overrun followed the same trend.

[3/] Cubic product scale is gross cubic scale adjusted for all defects expected to affect the yield of solid wood products.

Table 7—Lumber yield in percent of total lumber tally for sizes of ponderosa pine boards cut from two mills in the Black Hills

Lumber size	Average board foot volume	
	Mill A	Mill B
	- - - - Percent - - - -	
1 x 4	16	25
1 x 6	25	34
1 x 8	25	20
1 x 10	17	12
1 x 12	16	9

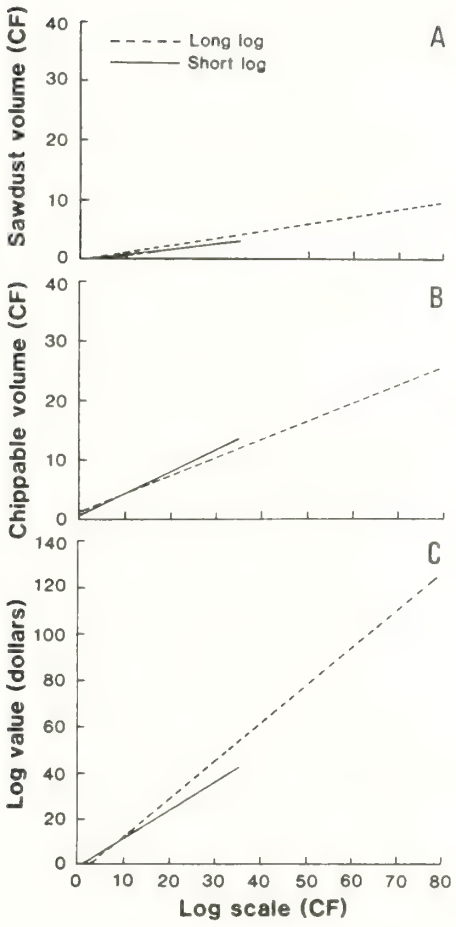

Figure 6.—Rough-green lumber volume, chippable volume, and sawdust volume, by cubic log scale, for ponderosa pine in the Black Hills. Cubic product scale is the basis for log volume: It is gross cubic scale reduced for all defects expected to affect the yield of solid wood products.

A. Long log (mill A):

$$y = -0.064 + 0.120(ft^3) .$$

Coefficient of determination = 0.94 and standard deviation from regression = 0.39.

Short log (mill B):

$$y = -0.392 + 0.102(ft^3)$$

Coefficient of determination = 0.94 and standard deviation from regression = 0.14.

B. Long log (mill A):

$$y = 1.179 + 0.304(ft^3)$$

Coefficient of determination = 0.71 and standard deviation from regression = 2.57.

Short log (mill B):

$$y = 0.696 + 0.362(ft^3) .$$

Coefficient of determination = 0.83 and standard deviation from regression = 0.84.

C. Long log (mill A):

$$y = -8.27 + 6.88(ft^3) .$$

Coefficient of determination = 0.94 and standard deviation from regression = 21.67.

Short log (mill B):

$$y = -6.51 + 5.96(ft^3) .$$

Coefficient of determination = 0.94 and standard deviation from regression = 7.89.

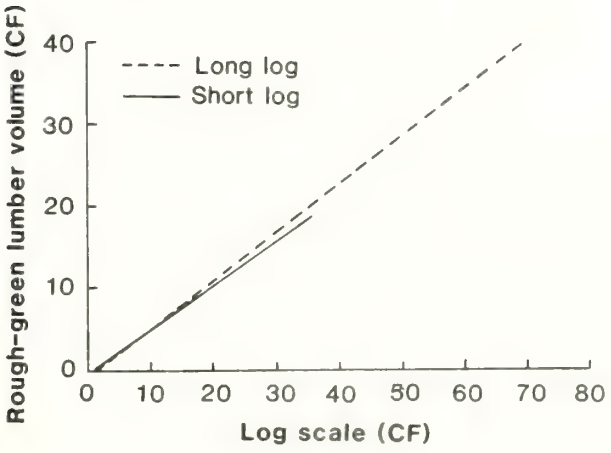

Figure 7.—Total lumber value of logs by cubic product scale for ponderosa pine in the Black Hills. Long log (mill A):

$$y = -4.63 + 1.65(ft^3) .$$

Coefficient of determination = 0.91 and standard deviation from regression = 6.76.

Short log (mill B):

$$y = -1.01 + 1.23(ft^3) .$$

Coefficient of determination = 0.87 and standard deviation from regression = 2.48.

Application

Repricing

Values of lumber were based on 1978 prices for White Woods[4] in the Black Hills and were furnished by the Rocky Mountain Region, USDA Forest Service. To adjust to current prices, simply multiply the predicted average value (that is, $/CCF or $/MLT) by the ratio of the new price of 1x6 No. 3 Common to the price of 1x6 No. 3 Common in this report ($200). For example, if the previous value of a 10-inch log was $198.33/MLT and the new value of 1x6 No. 3 Common was $250/MLT, then $198.33 multiplied by ($250/$200) gives a value of $198.33 × 1.25, or $247.91.

Predicting Timber Value

A common use of the information in the report is to estimate the value of a stand of timber; for example, a tract of timber is offered for sale that contains 1 million BF or 200,000 CF. Typically, the number of logs and volume by diameter class within a log grade would be provided from a cruise. In this example I will use a 10-inch diameter class and assume that all logs are the same grade. This diameter class contains 2,552 logs with a volume of 100,000 BF or 23,080 CF.

Overrun.—The estimated lumber recovery percent for a 10-inch log would be 122 (from table 3); therefore (100,000 BF) (1.22) = 122,000 BF of lumber. Using the equation in figure 3, the value of the 10-inch logs is:

$$\$/MLT = 195.46 + 1.61(10) = \$211.56; \text{ and}$$
$$\text{total lumber value} = \$211.56/MLT\ (122\ MBF) = \$25{,}810.32.$$

This procedure could be used for each diameter class and the sum of the diameter class values would equal the total value of lumber for the stand.

Cubic recovery percent.—To calculate the total value of the 10-inch logs on a CF basis, use the equation in figure 5. The calculation would be:

$$\$/CCF = 193.03 - 1144.49(1/10) + 3325.14(1/10^2) = \$111.83\ CCF; \text{ and}$$
$$\text{total value} = 111.83/CCF\ (230.80\ CCF) = \$25{,}810.36.$$

This procedure would also be done for each diameter class to obtain lumber value for the stand.

Direct Estimators.—With this method the value can be determined directly from log volume. Using the equation for the relationship shown in figure 7, the calculation would be:

$$\text{lumber value} = -1.01(\text{no. of logs}) + 1.23(CF), \text{ or}$$
$$\text{lumber value} = -1.01(2{,}552) + 1.23(23{,}080) = \$25{,}810.88.$$

Value of secondary products.—Secondary products such as chips or sawdust cannot be measured in BF but are often measured in CF or by weight. Estimating products directly from scale volume makes it easy to calculate chip and sawdust

[4] White Woods are Engelmann spruce, any true firs, any hemlocks, and any pines.

volumes. With these volumes it is possible to calculate the value of these products. For instance, the volume of chips for the 10-inch diameter class (2,552 logs) can be calculated using the proper equation from figure 6:

chip volume = 0.696(2,552) + 0.362(23,080 CF) = 10,130 CF (rounded).

If the price of chips were $60 per oven-dry ton or $0.03 per pound and the density were 24 pounds per CF,[5] there would be 243,120 pounds ((10,130 CF) (24 lb/CF)) of chippable fiber with a value of $7,293.60 ((243,120 lb) ($0.03/lb)). The value of the chips could be added to the value of the lumber and would result in a more accurate estimate of the total value of the 10-inch logs. The same procedure could be used to obtain a value for sawdust.

redicting Lumber olume by Grade

Information in this report could also be used to estimate the volume, by lumber grade, that could be produced from a group of logs. Suppose that in a deck of logs, there were 50,000 BF of 12-inch logs. Use table 3 to find the estimated recovery percent for 12-inch logs and multiply that percentage by the net log scale to find the estimated volume of lumber:

lumber volume = 50,000 (1.17) = 58,500 BF.

The final step is to multiply this lumber volume by the percent recovery expected for each lumber grade (table 4):

Molding and Selects	58,500 (0.04) = 2,340 BF
No. 2 and BTR Common	58,500 (0.06) = 3,510 BF
No. 3 Common	58,500 (0.64) = 37,440 BF
No. 4 Common	58,500 (0.23) = 13,455 BF
No. 5 Common	58,500 (0.03) = 1,755 BF

With volumes of lumber established for each lumber grade, the value can be determined by applying appropriate prices to these volumes. This procedure can be extended to include all diameter classes in the inventory. With this information a mill manager can select the log mix needed to fill particular orders and at the same time regulate the inventory.

Conversion Factors

It is often desirable to have log volumes estimated in cubic units. Cahill (in press) developed equations to convert Scribner board foot volume to cubic volume. The appropriate equation was tested on mill-length logs from one of the sale areas selected for this study. The estimate of the gross volume was the same as the actual gross volume; the product cubic volume was 2 percent higher. From this test it appears that Cahill's equation can be used to convert Scribner volume to cubic volume when applied to mill-length logs.

Metric Equivalents

1 inch = 2.54 centimeters
1 foot = 0.3048 meter
1 cubic foot = 0.02832 cubic meter
1 pound = 453.6 grams

[5] Oven dry weight per unit of green volume (Forest Products Laboratory 1974).

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Western Wood Products Association. Grading rules for western lumber. 4th ed. Portland, OR: Western Wood Products Association; **1977.** 202 p.

Glossary

Cubic recovery percent (CR %)—the cubic feet of lumber produced from a cubic foot of log input. Log volume can be expressed as a percentage of the gross, net (firmwood), or product (merchantable) cubic scale. Cubic recovery percent can be based on surfaced-dry as well as rough-green lumber.

Lumber recovery factor (LRF)—the board feet of lumber produced from a cubic foot of log input. As with cubic recovery percent, log input volume can be gross, net (firmwood), or product (merchantable) cubic scale.

Recovery percent (overrun)—the board feet of lumber produced from a board foot of net log scale expressed as a percentage. It is equal to overrun plus 100 percent. Although recovery percent has traditionally been expressed as a percentage of net Scribner scale, it can also be expressed as a percentage of gross Scribner scale.

Dollars per thousand board feet lumber tally ($/MLT)—the average value of the lumber produced, based on the lumber produced and the pricing structure used in this paper.

Dollars per hundred cubic feet of log scale ($/CCF)—the total value of the lumber produced from a log divided by the cubic scale of the log. Cubic scale volume may be gross, net (firmwood), or product (merchantable).

Plank, Marlin E. Lumber recovery from ponderosa pine in the Black Hills, South Dakota. Res. Pap. PNW-328. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. **1985.** 14 p.

A sample of 400 ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) trees was selected from each of two sale areas in the Black Hills National Forest, South Dakota. The logs were processed through two sawmills into 1-inch-thick boards. Estimates of volume and value recovery based on cubic volume and board foot volume are shown in tables and figures.

Keywords: Lumber recovery, lumber yield, ponderosa pine (Black Hills), *Pinus ponderosa*, South Dakota (Black Hills).

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Estimating the Weight of Crown Segments for Old-Growth Douglas-Fir and Western Hemlock

J.A. Kendall Snell and Timothy A. Max

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Abstract

Snell, J. A. Kendall; Max, Timothy A. Estimating the weight of crown segments for old-growth Douglas-fir and western hemlock. Res. Pap. PNW-329. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 22 p.

Equations were developed for predicting weight of continuous live crown, total live crown, dead crown, any segment of live crown, and individual branches for old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) trees. A branch method and a ratio method were developed for estimating the weight of crown segments. Equations were based on data from 32 Douglas-fir and 29 western hemlock trees from the Gifford Pinchot National Forest in southwestern Washington. An additional 49 Douglas-fir and 50 western hemlock were selected for validating the models.

For predicting weight of a segment of crown, the branch method was less biased and more accurate than the ratio method. The branch method is recommended for felled trees because it more easily accommodates the large amount of breakage in the crown of felled old-growth trees.

Keywords: Crown weights, estimates, moisture content (wood), old-growth stands, Douglas-fir, western hemlock.

Summary

The purpose of this study was to develop and validate estimators to predict total crown weight and weight of any segment of crown for old-growth felled and bucked Douglas-fir and western hemlock trees. Equations were developed for predicting weight of continuous live crown, total live crown, dead crown, any segment of live crown, and individual branches. A branch method and ratio method were developed for estimating the weight of crown segments. Equations were based on data from 32 Douglas-fir and 29 western hemlock trees from the Gifford Pinchot National Forest in southwestern Washington. An additional 49 Douglas-fir and 50 western hemlock were selected for validating the models.

For predicting weight of a segment of crown, the branch method was less biased and more accurate than the ratio method. The branch method is recommended for felled trees because it more easily accommodates the large amount of breakage in the crown of felled old-growth trees.

Variation in the amount of crown broken off during felling is a major practical problem in estimating the weight of crown that remains attached to logs or felled trees. The weight of crown remaining attached to old-growth Douglas-fir trees after felling ranged from 1 to 59 percent. (Crown breakage was not measured for western hemlock.)

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Introduction

Airborne and cable logging systems for yarding large trees in the west require large capital investments, and efficient, effective, and economical operation of these systems is critical. Further, more expensive, heavy-lift airborne logging systems are being developed; for example, the Heli-Stat (Piasecki Aircraft Corporation under contract with the USDA Forest Service and the U.S. Navy) and the Cyclo-Crane (AeroLift Inc.).[1] These new systems use lighter-than-air dirigibles to support the craft, motors, and wings that in turn provide thrust for lifting. For these logging systems or any other high-cost aerial logging system (such as helicopters) to operate efficiently, the weight of each payload must be as close to optimum as possible.

Because trees and logs cannot be weighed conveniently prior to hookup and transport, a method is needed to accurately estimate their weight after being felled and bucked. In the interest of logging residue cleanup and utilization, sometimes the crowns of trees are removed during yarding. Many models have been developed for predicting weight of crowns of western tree species (for example, Adamovich 1970, Brown 1978, Fujimori 1971, Fujimori and others 1976, Gholz and others 1979, Snell and Anholt 1981, Woodard 1974). These and other studies, however, do not provide prediction equations for weight of any segment of the continuous crown for old-growth trees between 14 and 157 cm in diameter at breast height (dbh). When trees are felled and bucked, the amount of crown on any one log will depend on at least two major factors: (1) location of the log in the tree relative to the crown, and (2) the amount of crown physically removed by felling the tree. Accurate weight estimates for both crown and bole may be required to achieve acceptable payloads when crowns are yarded with logs.

The objectives of this study were to develop and validate estimators to predict the total crown weight, as well as the weight of any segment of crown for old-growth felled and bucked Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) trees. For clarity, the developmental part of the study is referred to as MODEL BUILDING and the validation part as MODEL VALIDATION.

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[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U. S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

Population

The population for MODEL BUILDING was all qualifying Douglas-fir and western hemlock trees on three 2-ha areas in the Wind River Experimental Forest, Gifford Pinchot National Forest, Washington. Trees sampled were over 200 years old and their dbh ranged from 14 to 157 cm (table 1).

Some trees in the sample areas were excluded from the population if they had (1) sufficient decay in the upper merchantable bole to produce a spiked top, (2) excessive lean, (3) crown damage due to logging, (4) a forked merchantable bole, or (5) heavy mistletoe infection. These trees were excluded because they were not safe to sample (see Measurements section and fig. 1) and with excessive rot the upper bole would probably shatter during felling, making it impossible to yard the crown with the bole.

The population for MODEL VALIDATION was all qualifying Douglas-fir and western hemlock trees on a separate 8.1-ha stand in the Wind River Experimental Forest. Trees were excluded using the same criteria as for the population for MODEL BUILDING, except trees with excessive lean were not excluded as they did not have to be climbed for the validation part of the study.

Table 1—The frequency distribution of diameter at breast height (dbh) for the sample trees in the study area, Wind River Experimental Forest, Washington

	MODEL BUILDING		MODEL VALIDATION	
Dbh class	Douglas-fir	Western hemlock	Douglas-fir	Western hemlock
Centimeters				
10	—	—	--	1
20	—	—	—	2
30	—	2	1	2
40	—	2	2	7
50	—	4	5	5
60	2	5	1	4
70	3	3	6	5
80	2	3	5	5
90	4	6	4	6
100	3	2	11	2
110	3	2	3	5
120	3	—	4	4
130	4	—	6	1
140	2	—	1	1
150	5	—	—	—
160	1	—	—	—
Total	32	29	49	50

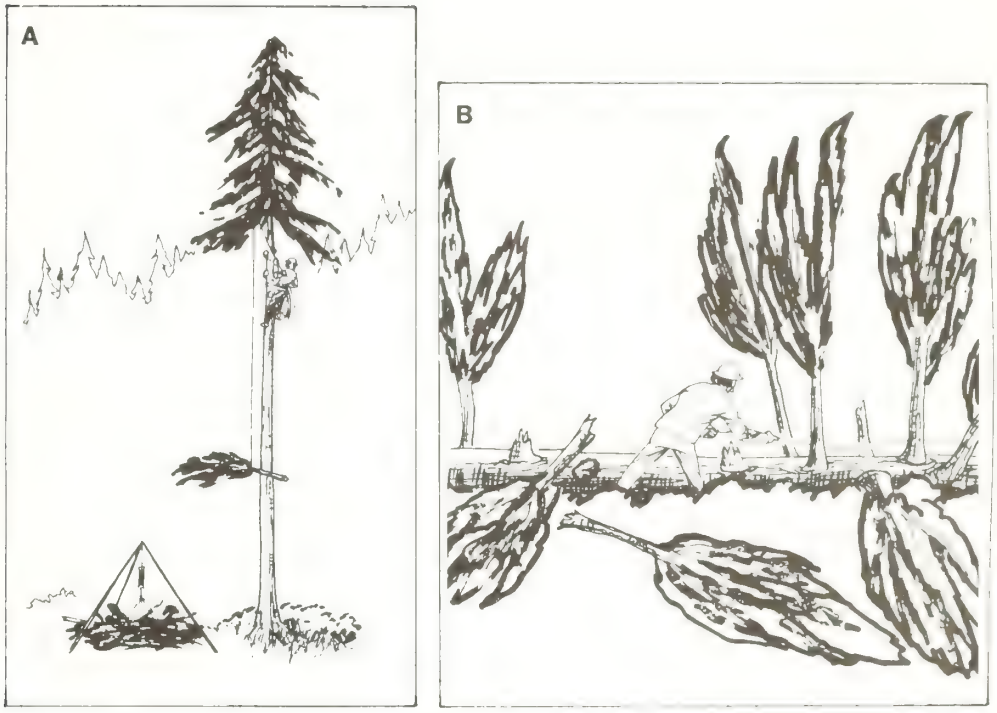

Figure 1.—Two data collection procedures were used in the study: (A) Trees were climbed and branches were carefully lowered when data were collected for MODEL BUILDING; (B) trees were felled and crown remaining after felling was measured for MODEL VALIDATION (note that breakage occurred during felling).

Methods

The two parts of this study, MODEL BUILDING and MODEL VALIDATION, used quite different approaches. Data for MODEL BUILDING were obtained by carefully removing each branch in the crown of sample trees while the trees were standing (fig. 1a). Branches were carefully dropped or lowered to the ground to accurately measure branch and crown weight. On the other hand, data for MODEL VALIDATION were collected under conditions similar to logging operations (fig. 1b) to test the applicability of the models in a realistic application. Trees were felled and models from the MODEL BUILDING phase were used to predict weights of segments of crowns to compare to the actual measured weights of these segments.

Sampling

Trees

For building the models, trees were selected from the population defined for MODEL BUILDING. All qualifying Douglas-fir and western hemlock trees were stratified by species and dbh; 32 Douglas-fir and 29 western hemlock were selected. Trees of each species were randomly selected within dbh classes, but the sample was distributed among dbh classes to obtain more of the larger trees. The diameter distribution of the trees in the MODEL BUILDING sample is given in table 1.

For validation of the models, a similar stratified sample was obtained from the population defined for MODEL VALIDATION; 49 Douglas-fir and 50 western hemlock were selected uniformly across the diameter classes. The diameter distribution of the trees in the MODEL VALIDATION sample is given in table 1.

Branches

Four sample branches were selected from each sample tree in the data set for MODEL BUILDING. These branches were needed to develop a prediction equation for branch weight from branch basal diameter and to estimate the proportions of branch weight in various classes of material; for example, needles and branch wood diameter classes 0-0.5 cm, 0.6-2.5 cm, etc. The four sample branches were selected as follows. The total number of branches and the maximum diameter of branches were estimated for each tree based on visual observations. The basal diameter range of branches was stratified into four diameter classes and the number of branches in each class was estimated. A random number was selected for each class that was less than the estimated maximum number of branches for that class. These random numbers were used to select one sample branch from each of the four diameter classes.

Four sample branches were also selected from each sample tree in the data set for MODEL VALIDATION. These branches were used to validate the prediction equations developed from the data set for MODEL BUILDING. One branch from each of the following diameter classes was selected from each tree:

Class	Range of basal diameter
	(Centimeters)
1	Less than 0.5
2	0.5 to 2.5
3	2.6 to 5.5
4	Greater than 5.5

Crown Sections

For MODEL BUILDING, the crown was separated into a maximum of 10 horizontal strata. The first strata was that portion below the continuous crown. The second to the tenth strata were in the continuous crown. Continuous crown is that part of the crown above where the internodal distance becomes regular and is less than 1.8 m and branches occur on at least three sides of the tree (fig. 2). Total crown includes the continuous crown plus all other live branches below the continuous crown. The length of these crown strata (sections) in the continuous crown varied, depending on internodal distances and the number of branches at each whorl. We tried to obtain a minimum of 10 to 12 branches and a crown section length of approximately 4 m. The number of sections ranged from 2 to the maximum of 10.

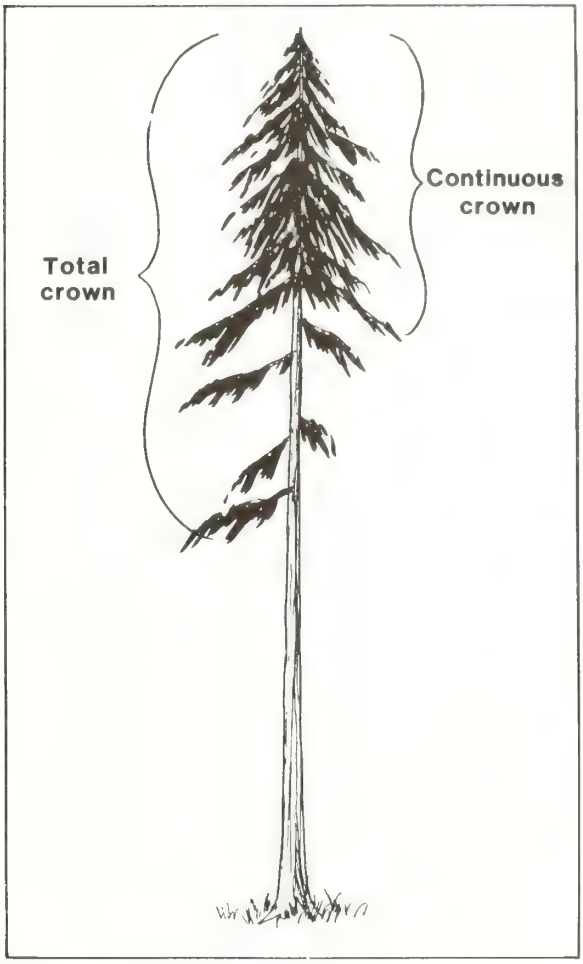

Figure 2.—Continuous crown is that part of the total crown above where the internodal distance becomes regular and is less than 1.8 m and branches occur on at least three sides of the tree.

For trees in the MODEL VALIDATION data set, only one section of crown was selected to be measured and used for validation. The sample crown section was restricted to be entirely within the continuous crown and not extend into the upper 10 percent of the continuous crown. For each species, the crown section was selected from the top one-half of the crown for one-half of the trees and from the bottom one-half of the crown for the other one-half of the trees. Assignment of top or bottom one-half was systematic. The actual location of the sample crown section was selected randomly within the top or bottom one-half of the crown. The length of the sample crown section was 4.6, 7.6, or 10.7 m depending on the length of the continuous crown in the sample trees; the longer the continuous crown the longer the sample section. Length of the sample section was restricted to be less than or equal to 50 percent of the continuous crown length

Measurements

Field

Small trees, shrubs, logs, and litter were cleared from the base as far out as crown diameter for trees in the MODEL BUILDING data set. Dbh, crown width, height to base of the live continuous crown, and total height were recorded.

A tree climber climbed the tree and measured the minimum branch basal diameter of each branch before sawing it from the bole (fig. 3). After removal, all limbs were grouped by crown section except that all dead limbs were grouped together. Each group of limbs, either a crown section or all dead limbs, was weighed in the field using a spring scale, and moisture samples were taken from each branch component.[2/]

The four sample branches in each tree were treated separately from the other branches. These sample branches were carefully lowered to the ground to prevent shattering and loss of material. They were physically separated into branch components and a moisture sample taken for each component.

For trees in the MODEL VALIDATION data set, basic tree measurements taken were dbh, total height, and height to base of continuous crown. The tree was then felled and a series of measurements were taken on the sample section of crown selected for validating the models. These measurements were:

1. Minimum basal diameter of all branches.
2. Estimated percentage of live branch weight lost because of breakage for whole crown and sample crown section.
3. Height from base of continuous crown to bottom of sample crown section.
4. Length of sample crown section.
5. Weight of all branches for which basal diameters were recorded.
6. Average percentage of moisture in crown section.

After the tree was felled, all live branches were removed from the sample crown section, chipped onto a tarp, and weighed to obtain green weight. Because the prediction models estimate dry weight, moisture content was determined for the section to compute actual dry weight. Two samples of the chipped material were selected to estimate moisture content for the section. Each sample was approximately 1 kg and contained a good mixture of foliage and wood from all sizes of branches.

Because the chipper could only chip material up to 10.2 cm in diameter, all branch material larger than 7.6 cm was weighed separately from the rest of the crown. Thin disks were cut from this material and placed in two airtight containers to obtain moisture content. The average moisture content from these samples was used to estimate dry weight of the crown section from green weight for this larger material.

[2/] Components are defined as follows: foliage and branch wood 0 to 0.5, 0.6 to 2.5, 2.6 to 7.5, and 7.6 cm and larger in diameter.

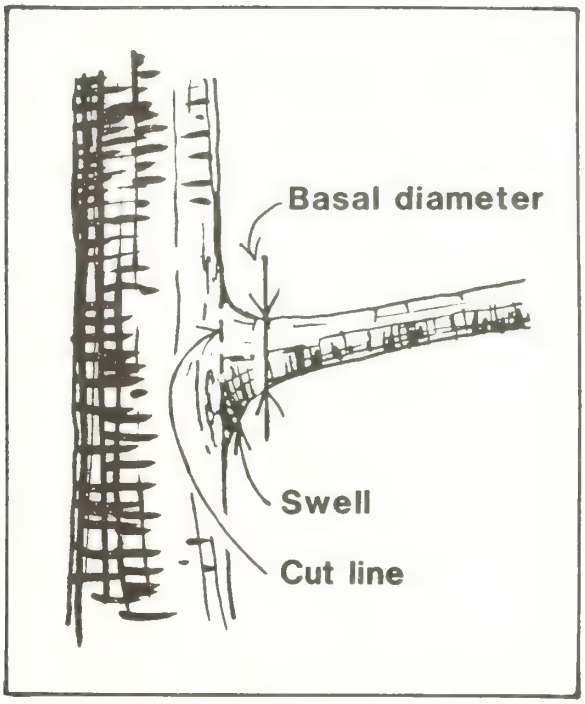

Figure 3.—Minimum branch basal diameter was measured outside swelling that occurs at the base of the branch.

Four sample branches from each tree were individually measured for minimum basal diameter, green weight, and moisture content. Dry weight was determined from green weight and moisture content. Moisture content was the average of two samples.

Laboratory

Green and dry weights were measured on all moisture samples to determine moisture content. For MODEL BUILDING, woody material larger than 0.6 cm in diameter was ovendried at 102 °C for a minimum of 15 hours (Ponto 1972). Foliage and woody material smaller than 0.6 cm in diameter were ovendried at 70 °C for a minimum of 15 hours. Foliage and the smaller branchwood were dried at the lower temperature to reduce the loss of volatiles. For MODEL VALIDATION, all chips were dried at 102 °C.

Determining Dry Weight

For the MODEL BUILDING data, an appropriate moisture content was needed to convert crown section green weight to ovendry weight because all analyses were done on ovendry weights. Other investigators (for example, Brown 1978) have reported that moisture content varies from bottom to top of crown as well as by size of material within the crown. We sampled foliage and four branchwood size classes (see footnote 2) and crown sections up the tree for moisture content. Table 2 gives the average moisture contents for foliage and branchwood size classes by species. We also determined the proportion, by weight, of these components based on their branch basal diameters. From this information, a composite moisture content was computed for converting green crown weight to ovendry weight. Ovendry weight was then used to develop regression equations for total continuous crown weight.

Table 2—Average moisture for foliage and branch wood of Douglas-fir and western hemlock by size class

Species and branch component	Number of samples	Average moisture content	Standard error of the mean
		Percent	
Douglas-fir:			
Foliage	117	100	1.2
Branch wood—			
0 to 0.5 cm	117	82	.9
0.6 to 2.5 cm	117	83	.8
2.6 to 7.5 cm	117	71	1.0
7.6+ cm	69	56	1.2
Western hemlock:			
Foliage	130	105	2.2
Branch wood—			
0.0 to 0.5 cm	130	77	1.1
0.6 to 2.5 cm	130	82	.8
2.6 to 7.5 cm	127	73	1.0
7.6+ cm	53	58	1.7

The composite moisture percent was calculated as follows:

1. The ovendry weights of sample branch components (leaves and branchwood diameter classes) were calculated using moisture samples collected from these components.
2. These weights were regressed separately on their branch basal diameters.
3. These regression equations were then used to estimate the weight of each component for every branch on each tree.
4. The weight of each component was summed for all branches within each crown section.
5. These component total weights for each section were used as weighting factors to estimate a composite moisture content for the section.

These composite moisture percentages were then used to convert the green crown section weight to estimates of ovendry weight. A similar procedure was used by Brown (1978) and suggested by Ek (1979).

Because all of the dead branch wood was separated into diameter classes, the moisture samples taken from each class were used to convert them to ovendry weight.

For the MODEL VALIDATION sample, composite 1-kg samples were selected from the chipped material, and sample disks were selected from branch parts larger than 7.6 cm. Two samples of each type of material were selected from each sample crown section and each sample branch. Moisture content was computed for each composite sample and group of sample disks as described above. The average of the two moisture contents was used to convert green weight to dry weight. Conversions were computed separately for the chipped material and branch wood larger than 7.6 cm.

Model Development

Three different approaches were tried for modeling weight of any segment of crown. The methods are the branch method, ratio method, and bole section method. These methods required development of prediction equations for weight of the continuous crown and individual branches. In addition, equations were developed for predicting weight of total live crown and dead crown.

Branch Method

The branch method uses a prediction equation to estimate weight of individual branches from their minimum basal diameter (Brown 1978, Ek 1979). Estimated weight of a crown segment is the sum of the estimated weight of all the branches in that crown segment.

There are several disadvantages to this method. The most important is the lack of compatibility between the estimated weight of segments and the estimated weight of the whole crown. These models are compatible if the sum of the estimated weights for all the segments of the crown equals the weight of the whole crown estimated by the model predicting whole crown weight. Using this method the combined weights of all crown segments does not equal the total crown weight, even though the crown segments completely subdivide the crown. A further disadvantage is that every branch basal diameter in the section must be measured or estimated. An advantage of the method is ease in adjusting for branches or parts of branches broken off during felling. Branches that are completely broken off are simply not measured. For partial branches the predicted weight is reduced using an estimate of the percent missing.

Ratio Method

The ratio method is based on two regression equations. The first predicts total continuous crown weight and the second predicts a ratio of weights. Ratios and lengths are illustrated in figure 4. The dependent variable is the ratio of crown weight between the bottom of the live continuous crown and any particular point in the crown to total continuous crown weight. The independent variable is ratio of length of the same lower crown section, beginning at the bottom of the live continuous crown, to total continuous crown length. The model is restricted so the dependent variable ranges between zero and one. The weight ratio for any crown segment not beginning at the base of the crown is determined by the difference in two ratios. The first weight ratio is for the part of the crown from the base of the continuous crown to the base of the crown section. The second ratio includes the part of the crown in the first ratio plus the crown section. The difference in these two ratios is the weight ratio for the section. The weight of this section is estimated by multiplying the estimated weight ratio by the total continuous crown weight. This approach is similar to volume ratio models developed to estimate volume of tree boles to any top diameter (Burkhart 1977, Cao and others 1980).

The advantage of this method is the compatibility of the resulting estimates. The ratio for the whole continuous crown is one, so the weight of the whole continuous crown is determined by the equation for predicting the whole continuous crown weight. The segments of the continuous crown completely subdivide the continuous crown so the sum of all the weight ratios for the segments is one. The sum of weights for all segments therefore equals the weight of the whole continuous crown.

The main disadvantage of this method is the measurements required. These measurements include total continuous crown length, length from the base of the continuous crown to the base of the crown section, and length of the crown section. These measurements are difficult to obtain in an operational environment.

Bole Section Method

The bole section method relates the weight of the crown segment to characteristics of the section of bole to which it is attached. Candidate independent variables were diameter of the small and large end of the bole section, diameters of the bole where the crown began and ended, and length of the crown segment. This method, like the branch method, is not compatible. The advantage of the bole section method is the simplicity of required measurements. Only log diameters and lengths are needed.

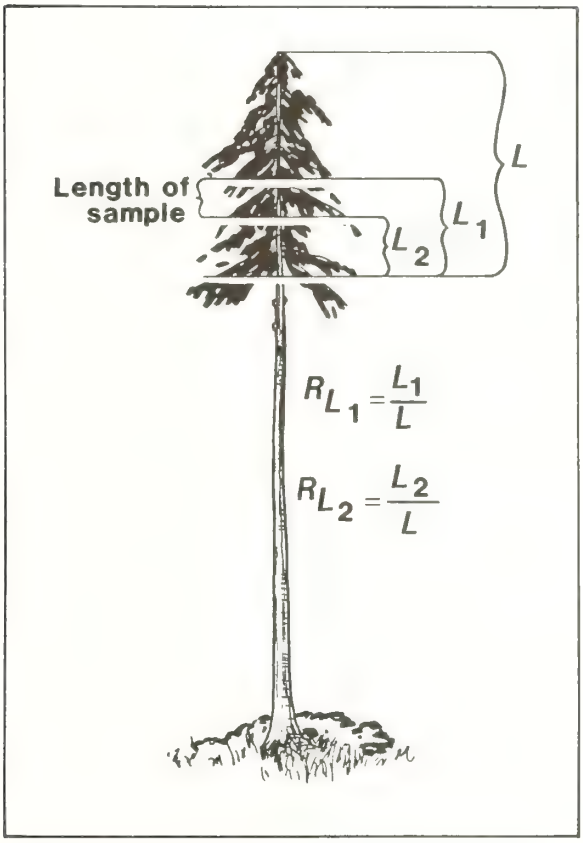

Figure 4.—Lengths of the parts of the crown used in the ratio method. *L* is the length of the continuous crown. Crown below the continuous crown has been removed. *L*2 is the length of the crown below the sample section. *L*1 is the length from the bottom of the live crown to the top of the sample section. Length of the sample section is *L*1 minus *L*2.

Model Estimation

Branch Method

The branch method is based on a regression equation for predicting weight of individual branches. The equations were developed from the MODEL BUILDING data. Several models were considered involving transformations of variables and slightly different equation forms. Selection of the final model was based on the coefficient of determination (R^2), standard error about regression ($s_{y.x}$), residual plots, and the desirability of having a common model for both species. The model selected was

$$\ln \hat{w}_B = A + B \ln(d);$$

where:

ln = natural logarithm,
$\hat{w}_B$ = estimated ovendry branch weight (kg),
A,B = regression coefficients, and
d = minimum basal diameter of branch (cm).

The results are summarized in table 3.

The validation data provided an opportunity to test the predictive ability of the equations for estimating weight of individual branches. Validation of the branch method for estimating weight of segments of crowns is described in the VALIDATION section. The following paragraph describes validation of just the equations for predicting weights of individual branches.

Data from MODEL VALIDATION sampling were used to validate the equations for predicting weight of individual branches. For each branch in the validation data the difference between the actual and predicted dry weight was computed. These differences were used to estimate bias and accuracy of the equations (table 4). Plots of these differences against branch diameter revealed that prediction error increased with branch diameter for both species. The equations for both species had relatively little bias.

Table 3—Regression equations for predicting ovendry weight of Douglas-fir and western hemlock branches

$$\ln \hat{w}_B = A + B \ln (d)^{1/}$$

Species	A	B	Number of samples	Mean square error	R^2
Douglas-fir	-2.7552	2.2150	128	0.15	0.96
Western hemlock	-2.6895	2.3254	116	.21	.96

1/ ln = natural logarithm, $\hat{w}_B$ = estimated branch ovendry weight in kilograms, A and B = regression coefficients, and d = branch basal diameter in centimeters.

Table 4—Predictive ability of the regression equations for predicting branch weight as determined from the MODEL VALIDATION data

Species	Bias[1/]	Mean absolute difference[2/]	Root mean squared difference[3/]
		Kilograms	
Douglas-fir	-0.06	0.27	0.62
Western hemlock	.02	.78	1.80

1/ Bias $= \sum_{i=1}^{n} (w_{Bi} - \hat{w}_{Bi})/n$;

where: n = number of branches,
w_{Bi} = observed weight of i^{th} branch, and
$\hat{w}_{Bi}$ = predicted weight of i^{th} branch.

2/ Mean absolute difference $= \sum_{i=1}^{n} |w_{Bi} - \hat{w}_{Bi}| /n$.

3/ Root mean squared difference $= \left[\sum_{i=1}^{n} (w_{Bi} - \hat{w}_{Bi})^2 /n \right]^{1/2}$.

Ratio Method

The ratio method used the MODEL BUILDING data to develop two prediction equations. One equation predicts total continuous crown weight. The other equation predicts a weight ratio; that is, the proportion of weight in any segment of crown.

For total continuous crown weight, candidate models were those proposed by other researchers (for example, Brown 1978, Gholz and others 1979, Schlaegel 1975). Only models that used dbh as the independent variable were considered. The final model was selected using the same criteria as in the branch method.

The model selected for total live continuous crown weight was

$$\ln \hat{w}_L = A + B \text{ (dbh)};$$

where:

ln = natural logarithm,
$\hat{w}_L$ = estimated ovendry weight of the live, continuous crown (kg),
A,B = regression coefficients, and
dbh = diameter at breast height (cm).

These results are summarized in table 5.

Weight ratios were plotted against the length ratios and variation seemed reasonably homogeneous, except near zero and one, where it approached zero. Several models were tried to relate weight ratio to length ratio. The models tried were similar to models used for volume ratios (Cao and others 1980). The final model was selected using similar criteria as for other models and was

$$\hat{R}_w = \exp\left(A\ (1 - R_L)^B\right);$$

where:

$\hat{R}_w$ = estimated ratio of crown segment weight to total continuous crown weight,
exp() = the base of natural logarithms (e) raised to the power in parentheses,
A,B = regression coefficients, and
R_L = ratio of crown segment length to total continuous crown length.

Nonlinear regression was used to fit this model and results are summarized in table 6.

Table 5—Regression equations for predicting ovendry weight of live continuous crown of Douglas-fir and western hemlock

$$\ln \hat{w}_L = A + B\ (\text{dbh})^{1/}$$

Species	*A*	*B*	Number of samples	Mean square error	R^2
Douglas-fir	3.9436	0.0203	32	0.16	0.71
Western hemlock	3.7943	.0341	29	.15	.80

1/ln = natural logarithm, $\hat{w}_L$ = estimated ovendry weight of live continuous crown in kilograms, *A* and *B* = regression coefficients, and dbh = diameter at breast height in centimeters.

Table 6—Regression equations for predicting weight ratio from length ratio for Douglas-fir and western hemlock crowns

$$\hat{R}_w = \exp(A\ (1-R_L)^B)^{1/}$$

Species	*A*	*B*	Number of samples	Mean square error
Douglas-fir	-3.5703	2.3831	125	0.0079
Western hemlock	-3.0364	2.2964	164	.0077

1/$\hat{R}_w$ = estimated weight ratio, crown section ovendry weight over total continuous crown ovendry weight, exp = the base of natural logarithms (e) raised to the power in parenthesis, *A* and *B* = regression coefficients, and R_L = length ratio, crown section length over total continuous crown length.

Bole Section Method

In the bole section method, the weight of crown attached to a section of bole was related to measured characteristics of the section. There were no strong relationships found and the bole section method was dropped from further consideration.

In addition to the models built for the branch and ratio methods, equations were also developed for total live and dead crown weight. The model selected for total live crown weight was

$$\ln \hat{w}_T = A + B \text{ (dbh)};$$

where:

ln = natural logarithm,
$\hat{w}_T$ = estimated total live crown weight (kg),
A,B = regression coefficients, and
dbh = diameter at breast height (cm).

A slightly different model was selected for total dead crown weight:

$$\ln \hat{w}_D = A + B \ln \text{(dbh)};$$

where:

$\hat{w}_D$ = estimated total dead crown weight (kg)
and other symbols are the same.

These regression models are summarized in table 7.

Table 7—Regression equations for predicting ovendry weight of total live crown and dead crown for Douglas-fir and western hemlock

Live or dead crown and species	*A*	*B*	Number of samples	Mean square error	R^2
Live crown:		$\ln \hat{w}_T = A + B\ (\text{dbh})$[1]			
Douglas-fir	4.0068	0.0206	32	0.14	0.73
Western hemlock	3.8886	.0338	29	.13	.82
Dead crown:		$\ln \hat{w}_D = A + B \ln (\text{dbh})$[1]			
Douglas-fir	-10.6294	3.2692	32	.25	.79
Western hemlock	-5.4241	2.2577	29	.24	.73

[1]/ln = natural logarithm, $\hat{w}_T$ = estimated ovendry weight of live total crown in kilograms, *A* and *B* = regression coefficients, dbh = diameter at breast height in centimeters, and $\hat{w}_D$ = estimated ovendry weight of dead crown in kilograms.

Model Validation

The VALIDATION DATA were obtained to provide independent estimates of bias and average prediction error for the branch and ratio methods. Each observation was the weight (w_i) of one section from each tree in the sample. The dry weights of these sections were predicted using both the branch and ratio methods. Differences were computed between the observed and predicted section weights using both methods of prediction. Bias and accuracy were estimated from these differences for each species (table 8).

The branch method is substantially less biased and more accurate than the ratio method for both species for this independent data set (table 8). This is not surprising as the branch method uses the diameters of all branches in the sample crown section, substantially more information about the particular crown section than is used in the ratio method.

The ratio method was substantially more biased and, therefore, less accurate for western hemlock than for Douglas-fir. Examination of the data revealed that much of this inaccuracy was caused by poor predictions of total continuous crown weight in large western hemlock trees. In the MODEL BUILDING data for western hemlock the largest dbh was 111.6 cm, and only three trees had a dbh larger than 100 cm. The slope of the prediction curve increased rapidly for a dbh larger than 100 cm. The MODEL VALIDATION data set contained 11 trees with diameters at breast height between 105 cm to 143 cm. The prediction equation appeared to substantially overestimate weight of total continuous crown for these trees. The results shown in parentheses in table 8 are with these 11 trees eliminated. Although eliminating these trees reduced bias and increased accuracy somewhat, the ratio method still did not compare favorably to the branch method. Because of the apparent inaccuracy in estimating total continuous crown weight for large diameter old-growth western hemlock trees, this method is not recommended for western hemlock with a dbh greater than about 100 cm.

Discussion

The trees in this study represented a very limited scope in sampling. The MODEL BUILDING data were from three small areas and the MODEL VALIDATION data were from one somewhat larger area nearby. Results are only strictly applicable to these sampled populations. We believe, however, that the results of this study are applicable to trees similar in age and size, and grown under similar conditions, at least in the Wind River Experimental Forest and in the Gifford Pinchot National Forest. Results could probably be applied with caution on a wider basis.

The amount of crown broken off during felling is a major practical problem in estimating the weight of crown that remains attached to logs or felled trees. Amount of crown broken off during felling was measured in our validation sample of old-growth Douglas-fir. In this case, an average of only 10 percent of total crown weight remained attached after the trees were felled. The range was from 1 to 59 percent. This large amount of breakage and the variation from tree to tree eliminates application of estimates from standing trees to felled trees. In many cases the weight of attached crown will be negligible relative to log or bole weight. The drag on lifting logs with pieces of crown attached could be affected more by limbs being pinned beneath other logs or trees than by the weight of the crown itself. Breakage of crowns was not measured for old-growth western hemlock but visual observations indicated it was less than for Douglas-fir but still substantial. We recommend using the branch method for predicting weight of crown attached to felled, old-growth trees because it more easily accommodates the large amount of breakage.

Table 8—Bias and accuracy of branch and ratio methods determined from MODEL VALIDATION data

Species and method	Bias[1]	Mean absolute difference[2]	Root mean squared difference[3]
	Kilograms		
Douglas-fir:			
Branch	-3.5	6.6	10.3
Ratio	-13.3	21.0	28.5
Western hemlock:			
Branch	-4.2	15.8	25.2
Ratio[4]	-88.6	93.7	152.1
	(-37.6)	(44.1)	(67.0)

[1] Bias $= \sum_{i=1}^{n} (w_i - \hat{w}_i)/n$;

where: n = number of sample crown sections,
w_i = observed weight of sample crown section, and
$\hat{w}_i$ = predicted weight of sample crown section.

[2] Mean absolute difference $= \sum_{i=1}^{n} |w_i - \hat{w}_i| /n$.

[3] Root mean squared difference $= \left[\sum_{i=1}^{n} (w_i - \hat{w}_i)^2/n \right]^{1/2}$.

[4] Values in parentheses are for the ratio method after 11 western hemlock with dbh larger than 108 cm were eliminated.

Example

An example is given illustrating the use of the developed prediction equations. Equivalent English measurements are given in parenthesis throughout this example. Suppose a 100-cm (39-in) Douglas-fir tree is felled and bucked, and one of the logs to be yarded has 10 m (32.8 ft) of continuous crown.

Application of the branch method is straightforward. The basal diameter of each branch attached to the log after felling is measured and used to predict the dry weight of the branch (fig. 5). The prediction equations used are given in table 3. Total weight of the crown section is the sum of the predicted weight of all the branches. This total weight is ovendry weight, which must be converted to green weight. Because moisture percent can change between areas, trees in the immediate area should be sampled to determine an applicable moisture percent.

For the ratio method the example is as follows: Before felling the 100-cm (39-in) Douglas-fir tree, the continuous crown length is measured at 30 m (98 ft). From measuring the tree on the ground, it is determined that the 10-m (32.8-ft) crown section to be yarded with the log is 7 m (23 ft) up the bole from the base of the continuous crown (fig. 6).

Total weight of the continuous crown is estimated using the equation for Douglas-fir in table 5. For dbh 100 cm (39 in), the estimate of total weight of the continuous crown is 393 kg (867 lb). To determine the weight of the 10-m (32.8-ft) crown section, two weights must be estimated. These two weights are the weight of the lower 7 m (23 ft) of continuous crown and the weight of the lower 17 m (56 ft) of continuous crown. Note the 17-m (56-ft) section consists of the 10-m (23-ft) section of interest plus the 7-m (23-ft) of continuous crown below this section. The difference between the weights of the 17-m (56-ft) section and the 7-m (23-ft) section is the estimated weight of the 10-m (32.8-ft) crown section of interest.

The computations are as follows. The first weight ratio is computed using a length ratio of 7/30 = 0.23 (that is, $R_L = 0.23$). Substituting $R_L = 0.23$ into the equation in table 6 for Douglas-fir results in an estimated weight ratio of 0.1473 ($\hat{R}_w = 0.1473$). Multiplying this weight ratio by the total weight produces an estimate of weight in the lower 7 m (23 ft) of continuous crown: 0.1473 x 393 kg = 58 kg (128 lb). The second weight ratio is computed from a length ratio of (7+10)/30 = 0.57. Using $R_L = 0.57$ provides an estimate of $\hat{R}_w = 0.62$. The estimated weight for the lower 17 m (56 ft) of continuous crown is 0.62 x 393 kg = 244 kg (538 lb). The difference in these two weights is the estimated weight of the 10-m (32.8-ft) crown section of interest; that is, 244 kg - 58 kg = 186 kg (410 lb). So the estimated dry weight of the 10-m (32.8-ft) crown section beginning 7 m (23 ft) from the bottom of the continuous crown is 186 kg (410 lb). This is dry weight which must be converted to green weight. For this example we used a moisture content of 90 percent. Green weight is then (1+0.9)(186) = 353 kg (778 lb).

When trees are felled, some limbs and parts of limbs will be broken from the bole. As discussed earlier, the loss in weight from breakage can be substantial. In applying these prediction methods, a visual estimate should be made of the percentage of branch or branches missing. These percentages are used to adjust estimated weights.

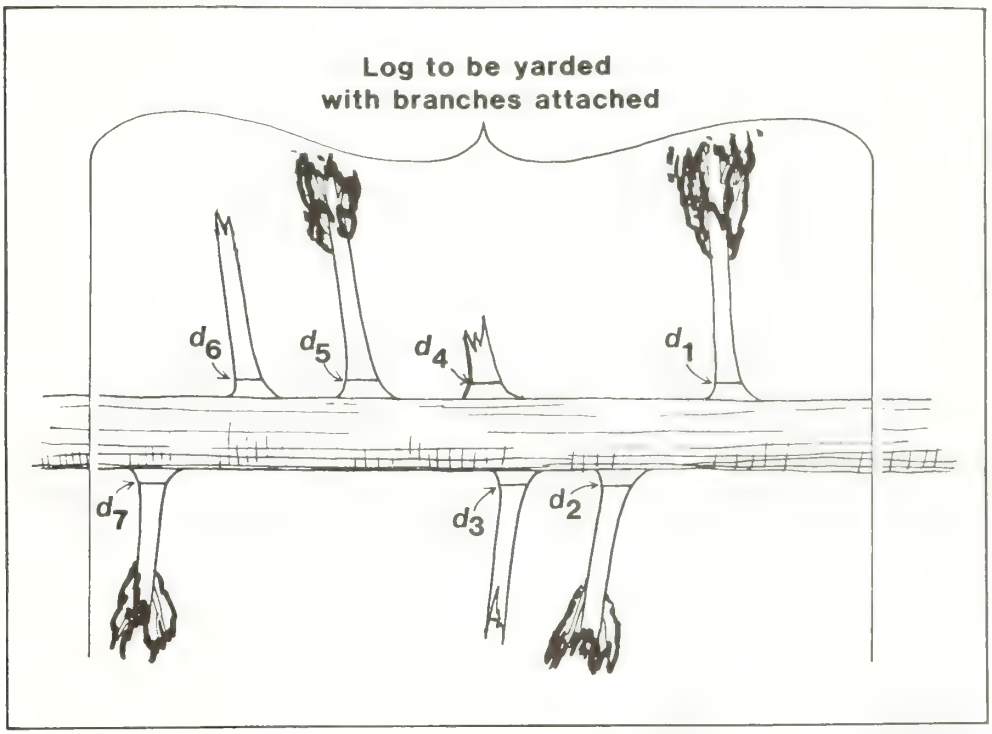

Figure 5.—Use of the branch method requires a measurement of basal diameter of all branches attached to the section of interest after the tree is felled.

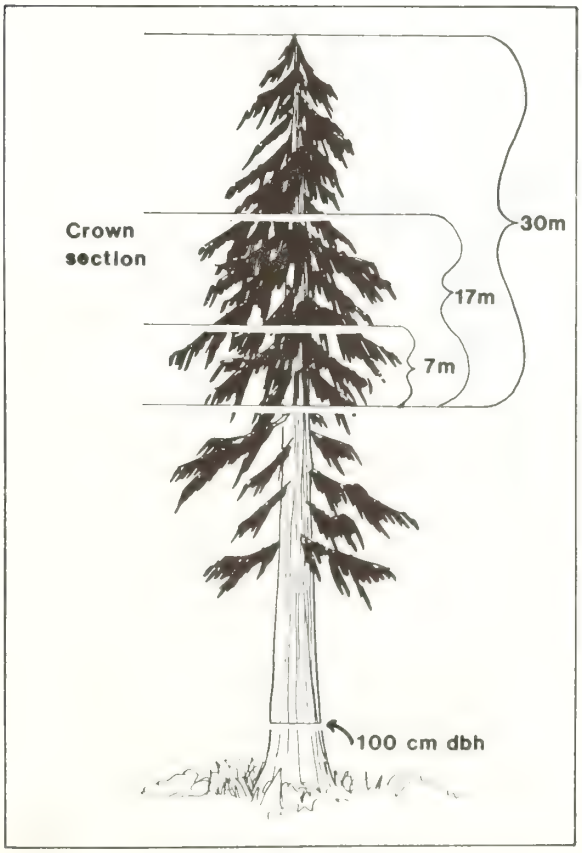

Figure 6.—Measurements needed to apply the ratio method.

Metric and English Units of Measure

When you know:	Multiply by:		To find:
Centimeters	0.394		Inches
Meters	3.281		Feet
Kilograms	2.205		Pounds
Hectares	2.471		Acres
Celsius	1.8	then add 32	Fahrenheit

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Equations were developed for predicting weight of continuous live crown, total live crown, dead crown, any segment of live crown, and individual branches for old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) trees. A branch method and a ratio method were developed for estimating the weight of crown segments. Equations were based on data from 32 Douglas-fir and 29 western hemlock trees from the Gifford Pinchot National Forest in southwestern Washington. An additional 49 Douglas-fir and 50 western hemlock were selected for validating the models.

For predicting weight of a segment of crown, the branch method was less biased and more accurate than the ratio method. The branch method is recommended for felled trees because it more easily accommodates the large amount of breakage in the crown of felled old-growth trees.

Keywords: Crown weights, estimates, moisture content (wood), old-growth stands, Douglas-fir, western hemlock.

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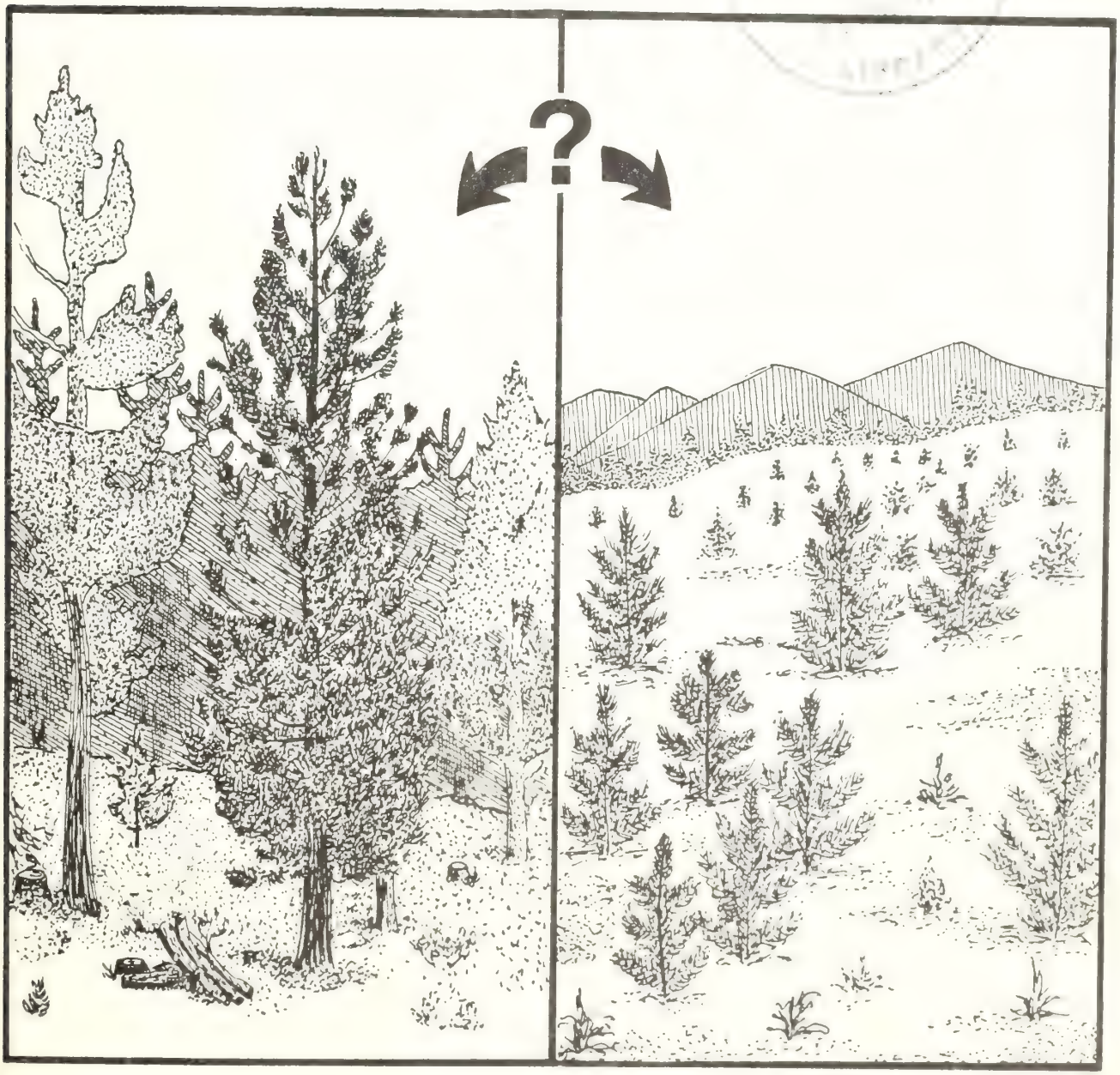
Research Paper
PNW-330
January 1985

Response of Dwarf Mistletoe-Infested Ponderosa Pine to Thinning:

1. Sapling Growth

James W. Barrett and Lewis F. Roth



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Abstract

Barrett, James W.; Roth, Lewis F. Response of dwarf mistletoe-infested ponderosa pine to thinning: 1. Sapling growth. Res. Pap. PNW-330. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 15 p.

Observations of thinned ponderosa pine infested with dwarf mistletoe over a 17-year period suggests that on average or better sites most infested stands can be managed to produce usable wood products in reasonable time, if trends found in juvenile stands continue.

Keywords: Thinning effects, western dwarf mistletoe, stand density, precommercial thinning, ponderosa pine, *Pinus ponderosa*.

Research Summary

No difference in rate of growth was found when plots of healthy ponderosa pine saplings thinned to 250 trees per acre were compared to similar plots parasitized by dwarf mistletoe. Abundance of mistletoe on individual trees increased progressively during the first 10 years of observation. After a second thinning and understory vegetation control on infested plots, height growth was good and dwarf mistletoe plants remained largely limited to lower portions of tree crowns.

Results indicate that parasitized ponderosa pine saplings can be managed by wide spacing that increases tree height growth in spite of abundant dwarf mistletoe. As long as rapid increase in height continues, this treatment will produce trees with healthy upper crowns and an acceptable rate of growth. Managing infested stands to complete the rotation may be a preferable alternative to clearcutting, site preparation, and planting.

Preface

Retarded growth and consequent prolonged timber harvest rotations are the most damaging effects of western dwarf mistletoe (*Arceuthobium campylopodum*) Engelm.) on ponderosa pine (*Pinus ponderosa* Laws.) forests in the Pacific Northwest. The seriousness of growth loss depends primarily on the abundance of dwarf mistletoe and its location in the crown, spacing of trees, the competition between trees and other vegetation for moisture, and site quality. These factors may act alone but usually interact.

Stands with heavy infestations of mistletoe on poor sites probably will not respond to silvicultural treatment, whereas lightly infected stands on good sites may need no treatment. Few stands fall into either category. The majority of stands, containing thousands of acres, have infestations that vary considerably in severity. The question is whether these stands are treatable, and, if they are, which stands should be treated, how, and when.

Most recent guidelines for mistletoe management of sapling and small-pole stands apply to dwarf mistletoes in general and do not provide the basis for critical decisions about a specific host species. Field observations over the last 25 years and results of long-term studies now provide realistic treatment possibilities in pure stands of ponderosa pine in the Pacific Northwest.

Dwarf mistletoes differ from most forest diseases in that the dispersal range of their seed—unlike that of fungal spores—is limited and predictable, and mature mistletoe plants are easy to see. Efforts to eradicate the pest have often proved unsuccessful because numerous large mistletoe plants appear within a few years of treatment, even though the stand work has been thorough. In thickets of slow growing pines, many invisible plants under the bark are missed at the time of treatment. Like their hosts, these hidden plants respond vigorously to thinning and develop fruitful aerial shoots. This habit of resurgent growth has discouraged dwarf mistletoe control in ponderosa pine in the Pacific Northwest.

Following an intensive evaluation of mistletoe in the varied natural stands in the Pringle Falls Experimental Forest on the Deschutes National Forest in central Oregon, Roth suggested that dwarf mistletoe in saplings and small poles could be tolerated through a rotation if stands could be silviculturally treated so as to maintain 10 inches or more of height growth each year.[1] Comprehensive study of mistletoe propagation by Roth and analysis by Strand and Roth (1976) disclosed that 10 inches did in fact approximate the lower theoretical level at which infested trees could maintain progress toward completion of a productive rotation without being overcome by mistletoe. This knowledge suggested that silvicultural maintenance of good height growth was an alternative to eradication of dwarf mistletoe.

Evidence was needed to determine (1) that the minimum growth of 10 inches could be achieved in infested stands, (2) that mistletoe, responding to increased tree vigor, would not offset the gain. This paper examines the effects of thinning on ponderosa pine saplings parasitized by western dwarf mistletoe. Data are from permanent sample plots. A companion paper (Roth and Barrett 1985) examines the effects of thinning on the dwarf mistletoe itself.

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[1]Roth, Lewis F. Unpublished data on file, Oregon State University, Department of Botany and Plant Pathology, Corvallis.

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Introduction

Natural multistoried stands of ponderosa pine (*Pinus ponderosa* Laws.) in the Pacific Northwest are usually harvested and managed by (1) clearcutting and planting, (2) some form of selection cutting, or (3) removing the overstory and thinning the sapling or pole understory. The first method is used infrequently because of environmental and other constraints. The second and third methods cause disease and management problems in the many locations where western dwarf mistletoe (*Arceuthobium campylopodum* Engelm.) infects all but the smallest trees.

Frequently, dwarf mistletoe infests both the mature overstory and the understory in ponderosa pine stands. Harvest of the infested overstory to eliminate that source of the pest is generally accepted practice; however, the ability of the parasitized understory trees to respond positively to thinning has not been demonstrated.

A crop of dwarf mistletoe seed is usually disseminated each autumn by plants in the parasitized overstory trees. Many of these seeds shower down on needles of the understory. After light rain, the hygroscopic seeds slide down the needles and lodge on the fascicle sheath or the stem in the axil of the fascicle. Seeds germinate the following spring, and the primary "rootlet" penetrates the thin bark to form an absorption system in the tree tissues. In 4 to 6 years aerial shoots appear, flower, and produce seeds. Thus, a base is established for spread and proliferation of the parasite in the pine reproduction even after the overstory source of the parasite has been removed.

Some pine understories are infested more heavily than others, the extent depending largely on past seed production by dwarf mistletoe plants in the overstory trees.

Retarded growth is the most damaging influence of dwarf mistletoe, especially when plants are abundant. Tree growth also is greatly affected by stand density. Infested, unmanaged understories often grow poorly, while dwarf mistletoe in stands that have been thinned and sanitized may resurge so conspicuously as to cast doubt on the merits of silvicultural treatment.

A number of workers have reported the adverse effects of western dwarf mistletoe in unmanaged, mature, and overmature stands (Childs and Edgren 1967, Childs and Wilcox 1966, Weir 1916). Shea (1964) reported significant reduction in growth of small trees heavily parasitized by dwarf mistletoe but found growth reduction difficult to detect in moderately parasitized trees. Roth (1971) found that the amount of damage from dwarf mistletoe plants was strongly influenced by the amount of competing vegetation. He thought it reasonable to expect improvement in growth of a parasitized stand following thinning, not just because the amount of dwarf mistletoe was reduced but also because growing conditions for the remaining trees were improved.

The consistent increase in diameter growth of young, uninfected ponderosa pine after thinning of high density stands is repeatedly reported in the literature (Barrett 1970, 1972, 1982; Mowat 1953). Barrett (1982) also observed increased height growth of formerly suppressed, sapling-sized ponderosa pines with wide tree spacing.

There are few published data from the Pacific Northwest to evaluate management, after overstory removal, of infested, sapling-sized ponderosa pine to validate existing guidelines[2] for stand treatment, or to verify impressions of dwarf mistletoe occurrence and damage.

This paper compares growth data from thinned plots in a stand of trees parasitized by dwarf mistletoe and adjacent thinned plots of healthy trees. The results support the validity of existing guidelines for managing dwarf mistletoe in National Forests of the Pacific Northwest. In addition, the paper suggests ways to evaluate treatment success in thinned, dwarf mistletoe-infested ponderosa pine stands.

The Study

In 1957, six plots were established in an overmature stand of ponderosa pine with a sapling understory. Both overstory and understory were infected by dwarf mistletoe. Each plot was a rectangle 79.2 by 105.6 feet (0.192 acres) surrounded by a 33-foot buffer strip. Each inner plot contained 192 mil-acre subplots that were used for sampling sapling characteristics before thinning.

The overstory contained about 25 thousand board feet per acre of mature and overmature ponderosa pine. The understory consisted of 40- to 70-year-old ponderosa pine saplings. Site quality, according to Meyer (1961), was site IV, or 78 feet at 100 years of age.

Before overstory removal and thinning, the following characteristics of the sapling understory were sampled on 12 mil-acre subplots in each sample plot:

1. Tree density
2. Average diameter
3. Average height
4. Number of infested trees
5. Number of visible plants per tree
6. Number of visible plants in the top half of the crown
7. Number of plants on the bole.

The overstory was carefully harvested, then each plot was thinned to 250 trees per acre or 48 trees per plot. The half-chain buffer strips were thinned to a similar density. A system of ropes was used to give each plot a grid and provide for as uniform spacing of leave trees as possible. At each grid position a tree was marked as a leave tree. Trees chosen had to be within one-third of the spacing distance or 4.5 feet from a grid point. On the infested plots if there was a choice between a visibly infested tree and a noninfested tree, the infested tree was kept, although severely infested trees (class five and six, Hawksworth 1977) were not chosen. If there were not infested trees at a grid point, then an uninfested tree was kept.

Six plots adjacent to the infested area, but without dwarf mistletoe, were logged and the understory thinned exactly the same way. The best tree at each grid point was left.

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[2]From "Silvicultural Examination and Prescription Handbook", Pacific Northwest Region, Forest Service, U.S. Department of Agriculture, Portland, Oregon. 1979

All 48 trees in each plot were tagged at breast height. Periodic measurements on all trees included d.b.h. to the nearest 0.1 inch and total height to the nearest 0.1 foot. Twelve trees on each plot were either climbed and measured or measured with a Barr and Stroud optical dendrometer for computing a volume equation of the form Volume = a + b D^2 H, where D = diameter breast high (inches), H = total height (feet). All trees from all plots were pooled to form one volume equation for each period. In addition, the following information was recorded for each of the 48 trees per plot during the 10-year period from 1959 to 1969:

1. Crown length
2. Crown density
3. Crown vigor
4. Number of visible plants in the top half of the crown
5. Total number of visible plants per tree
6. Total number of branches
7. Total number of branches bearing visible plants.

The principal objective at the time the study was established was to determine the magnitude of growth reduction caused by dwarf mistletoe in thinned, infested stands of ponderosa pine. In addition, we wanted to follow population trends of the parasite, over time, in individual trees and in the stand.

A second thinning was done to see if the remaining trees could be stimulated to grow in height faster than dwarf mistletoe moved up in the crown. Tree growth and dwarf mistletoe development were observed during 10 growing seasons from 1959 to 1969 at a density of 250 trees per acre. After analyzing growth of infested and uninfested plots during the 1959-to-1969 period, reviewing work by Strand (1973) and Strand and Roth (1976) on dwarf mistletoe population changes, and Barrett's (1970) observations of height growth in healthy stands, Roth suggested that the six infected plots be rethinned in the fall of 1971 to densities of about 90 trees per acre. In addition, pine manzanita (*Arctostaphylos patula* Greene), snowbrush (*Ceanothus velutinus* Dougl. ex Hook.), and bitterbrush (*Purshia tridentata* (Pursh) DC.) on the site were sprayed with herbicide to reduce brush competition and give the remaining trees further opportunity to grow. After the second thinning, growth and dwarf mistletoe development were observed for 11 growing seasons.

The uninfested plots were not thinned a second time because we wished to reserve trees at the 250-tree density for another purpose.

Results

Stand Characteristics Before the First Thinning

Before thinning, the plots contained about 8,000 saplings per acre. Trees averaged 0.7 inch d.b.h. and 7.5 feet high, with an average crown length of 3.0 feet, or a 40-percent crown ratio. An average of 2,600 trees per acre (32 percent) were visibly parasitized by dwarf mistletoe on the six infested plots. Twenty-two percent of these had visible infestations on the bole, and 20 percent had dwarf mistletoe in the top half of the crown.

Stand Characteristics After the First Thinning and 10 Years Later

Visibly parasitized trees increased from 74 to 89 percent in the 10-year period after the first thinning (table 1). Most plants that later appeared on "unparasitized" trees probably were present prior to 1959 (Roth and Barrett 1985). These latent infestations became visible 3 to 5 years after overstory removal and thinning. The average number of visible plants per parasitized tree increased dramatically from only four in 1959 to 36 in 1969.

Table 1—Average tree and stand characteristics of 6 uninfested plots and 6 infested plots of ponderosa pine saplings directly after thinning in 1959 and 10 growing seasons later

Stand and year	Trees per acre	Diameter at breast height	Height	Volume	Trees with mistletoe	Trees with 1/ plants on stem	Trees with plants in the top half of the crown
		Inches	Feet	Cubic feet	- - - - - - - - - - - - Percent - - - - - - - - - -
Uninfested:							
1959	250	1.8	10.3	33.6	--	--	--
1969	249	4.3	15.1	210.6	--	--	--
Infested:							
1959	250	1.9	11.4	37.7	74	56	38
1960	244	4.6	16.3	243.3	89	61	47

1/ Plants on branches within 4 inches of the main stem were considered as potentially on the stem.

Average dimensions of trees in the infested and uninfested stands were similar in 1959 (table 1), although trees in the infested plots averaged slightly larger. Diameter growth during the first decade of observation averaged 2.5 inches for trees in the uninfested plots and 2.7 inches for the infested plots (fig. 1). Tree height growth averaged 4.8 feet for the uninfested plots and 4.9 feet for the infested plots during the decade (fig. 2). As might be expected from figures for diameter and height growth, volume increment averaged slightly higher on the infested plots (fig. 3). There was considerable variation from plot to plot (figs. 1, 2, and 3) and, although averages are larger on the infested plots, an analysis of variance indicated no statistical difference between diameter, height, and volume increment on the respective plots. Trees on infested plots were slightly higher initially. Therefore, a separate covariance analyses was done for each 1959 variable: diameter, height, and volume. A nonsignificant portion of the growth variance was accounted for by these covariants.

Only six trees died out of 288 on the six infested plots. None of the trees that died was heavily parasitized by dwarf mistletoe, but trees that died were below average height and diameter and had short, low-density crowns. This loss amounted to only about 3 percent of gross increment. Only one tree on the uninfested plots died and it was low in vigor.

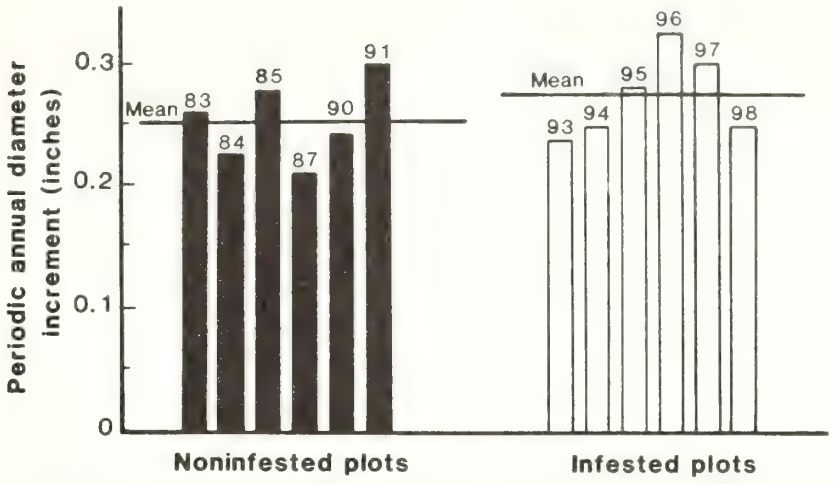

Figure 1.—Periodic annual diameter increment of plots from 1959 to 1969, when stand density was 250 trees per acre.

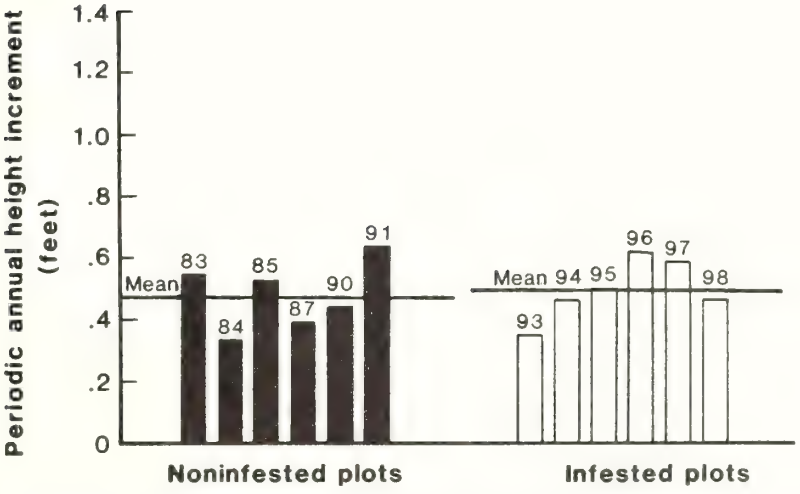

Figure 2.—Periodic annual height increment of plots from 1959 to 1969, when stand density was 250 trees per acre.

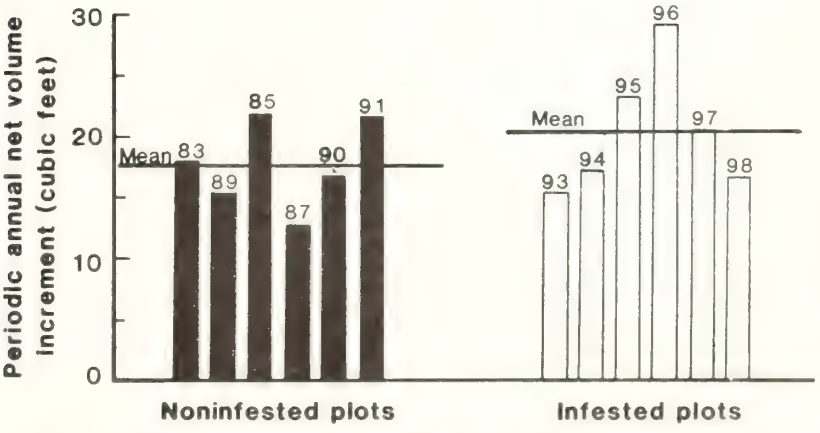

Figure 3.—Periodic annual net volume increment of plots from 1959 to 1969, when stand density was 250 trees per acre

Stand Characteristics After the Second Thinning

In the fall of 1971, the six infested plots were further thinned to an average of 88 trees per acre.

When infested plots were thinned the second time, the best trees were left, regardless of the amount of dwarf mistletoe they bore. Competing brush was suppressed with herbicides to give the remaining trees further opportunity to grow well. Growth on these trees was observed during eleven growing seasons from spring 1972 through fall 1982 (table 2).

Table 2—Stand characteristics of the 6 plots infested with dwarf mistletoe after the second thinning in 1972 and 11 growing seasons later in the fall of 1982

Plot number	Trees per acre	Diameter at breast height		Height		Volume 1/	
		1972	1982	1972	1982	1972	1982
		- - - - Inches - - - -		- - Feet - -		- Cubic feet -	
93	89	5.71	8.69	20.2	31.4	149.0	426.0
94	89	5.96	10.12	21.2	37.2	155.0	630.6
95	94	6.49	10.12	23.9	38.3	199.8	709.7
96	99	6.96	10.67	24.6	38.9	265.8	765.5
97	78	6.35	10.23	22.6	37.2	150.8	567.9
98	78	5.80	9.52	20.9	34.0	126.8	482.0
Average	88	6.2	9.9	22.2	36.2	174.5	597

1/Total volume from ground to tip of tree.

Diameter growth rate on trees left after the second thinning remained surprisingly similar to that observed on the same trees during the first decade while they were part of the 250-trees-per-acre stand (fig. 4). Rate of height growth, on the other hand, increased after the second thinning, and these same trees grew an average 1-1/4 feet each year on five of the plots and 1 foot on one plot (fig. 5). The same trees grew only an average of 0.7 foot from 1959 to 1969 after the first thinning. Annual height growth on the uninfested plots, however, also increased about 0.9 foot from 1972 to 1982. We can attribute a portion of this increased rate of height growth after the second thinning to additional release both from trees and brush, but it is also substantially a function of greater time since the first thinning (Barrett 1973). This increase in rate of height growth played an important part in the volume increment that accumulated after the second thinning (fig. 6). Although this appears to be a notable increase in volume increment from one period to another, it should be kept in mind that current annual volume increment in a released young stand such as this rises rapidly in the first several decades after treatment. The uninfested plots that still maintained 250 trees per acre during this 11-year period grew about 60 cubic feet per acre per year because of the additional time at the higher density and thus a greater growing stock base, while the rethinned infected plots grew about 38 cubic feet per acre per year. This is not a totally legitimate comparison, however, because we did not rethin the uninfected plots, but it helps compare growth in the two stands.

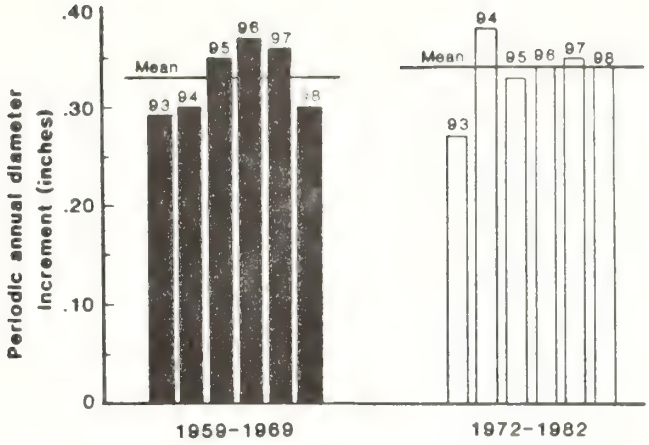

Figure 4.—Periodic annual diameter growth of trees in infested plots kept through both thinnings, during the first decade at a stand density of 250 trees per acre and during the second period at 88 trees per acre

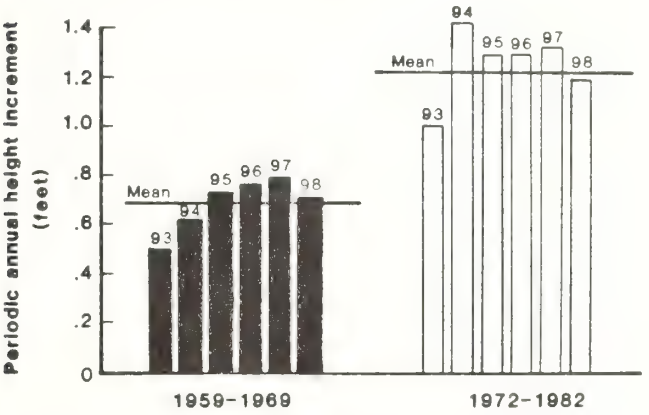

Figure 5.—Periodic annual height growth of trees in infested plots kept through both thinnings; during the first decade at a stand density of 250 trees per acre and during the second period at 88 trees per acre

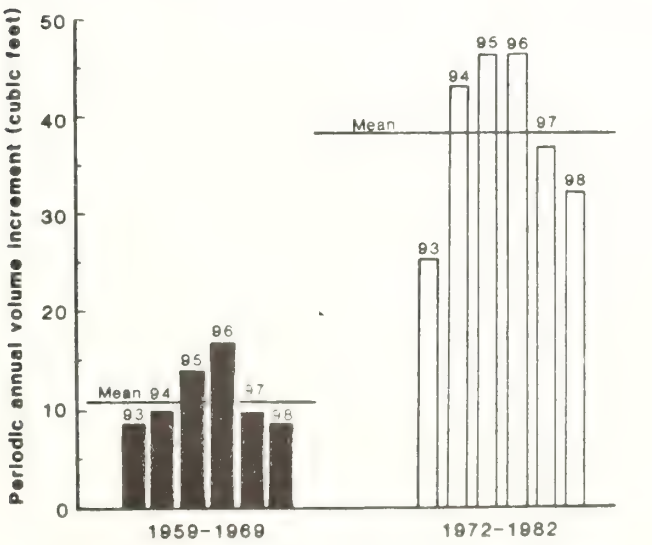

Figure 6.—Periodic annual volume growth of trees in infested plots kept through both thinnings; during the first decade at a stand density of 250 trees per acre and during the second period at 88 trees per acre

Discussion and Application

This study indicates that, for at least a decade, moderately infested stands of sapling-sized ponderosa pine thinned to 250 trees per acre will produce as much wood as healthy stands thinned to the same density. This is not a new idea, because Shea (1964) and Belluschi (Shea and Belluschi 1965), working with individual tree growth rather than per acre wood production, found significant reductions in diameter growth only in "severely" infested trees.

This study and other work (Barrett 1973) shows that height growth of individual trees, whether parasitized by dwarf mistletoe or not, may be increased by regulating stand density and further augmented by controlling understory vegetation. General observation of the study area 11 years after the second thinning shows trees to be growing well over 10 inches in height per year in spite of heavily parasitized lower branches (fig. 7). The appearance of abundant mistletoe in the lower crowns is disturbing to forest managers until they look closely at the growth in height and diameter that is taking place (figs. 8 and 9). One must conclude from the performance of these trees that good height and diameter growth can be maintained for several decades and that considerable dwarf mistletoe may be tolerated in a managed stand.

Figure 7.—General view of a twice-thinned infested stand in 1983

Figure 8.--Although these trees have heavily parasitized lower crowns they are growing more than 1 foot in height annually.

Figure 9.—The lower crown of this tree is heavily parasitized, yet height and growth diameter are good.

If sustained good height growth is a primary mitigator of dwarf mistletoe damage, fertilization—an additional management choice—may be available to limit loss in parasitized thinned stands. Cochran (1979) reports a 50-percent increase in height growth in thinned fertilized plots as compared with unfertilized plots. He fertilized a thinned stand of small poles at rates equivalent to 200 pounds of nitrogen, 100 pounds of phosphorus, and 33 pounds of sulfur per acre. These elements were applied in the form of ammonium sulphate, urea, and triple super phosphate. The time over which this treatment will be effective is not yet known. The effect of fertilization on the mistletoe also is unknown. We would expect plants to become more fruitful but would not expect this increase to offset benefits from improved growth in tree height. Fertilization of infested stands should be undertaken with discretion. It might be highly appropriate for special use areas such as campgrounds.

It should be recognized that acceleration of height growth in thinned suppressed sapling stands was not immediate. Response of well chosen trees on good to average sites is delayed 3 to 5 years after thinning. Growth peaks in 8 to 12 years (Roth and Barrett 1985). The magnitude of the growth response is related to stand density. As shown in figure 10, height growth in a healthy stand of 125 trees per acre does not exceed 10 inches per year until 8 to 12 years after thinning. If understory vegetation is controlled, making more soil moisture available to the trees, this desirable rate of height growth may be achieved sooner. Trees under intensive management should maintain the desired increment rate for a substantial portion of present day rotations (Barrett 1978).

A companion paper (Roth and Barrett 1985) shows that height growth has a notable effect on the distribution of dwarf mistletoe within the tree. A review of what was done in that study shows how infected stands can benefit from thinning. First, 250 trees per acre were left after overstory removal and the first thinning. This is more than are usually left when the sawlog market is the target for the first commercial entry. This is also a high stocking level that can lead to spread of dwarf mistletoe (Strand and Roth 1976). Second, trees parasitized by dwarf mistletoe were deliberately left in the first thinning. Consequently, in the first thinning we created a less desirable management situation than if we had left fewer trees and had discriminated against trees parasitized by dwarf mistletoe. Even so, growth was not reduced by dwarf mistletoe during the decade after thinning. In the second thinning we regulated density so that trees were widely spaced but the number per acre that had average diameters was above the minimum stocking-level curve (Barrett 1979) on all plots (table 2).

If density had been reduced in the first thinning to between 100 and 140 trees per acre that appeared free of dwarf mistletoe or were only moderately parasitized, and then if the undesirable trees had been harvested a decade later, would we have created a stand that would produce volume comparable to that of uninfested stands?

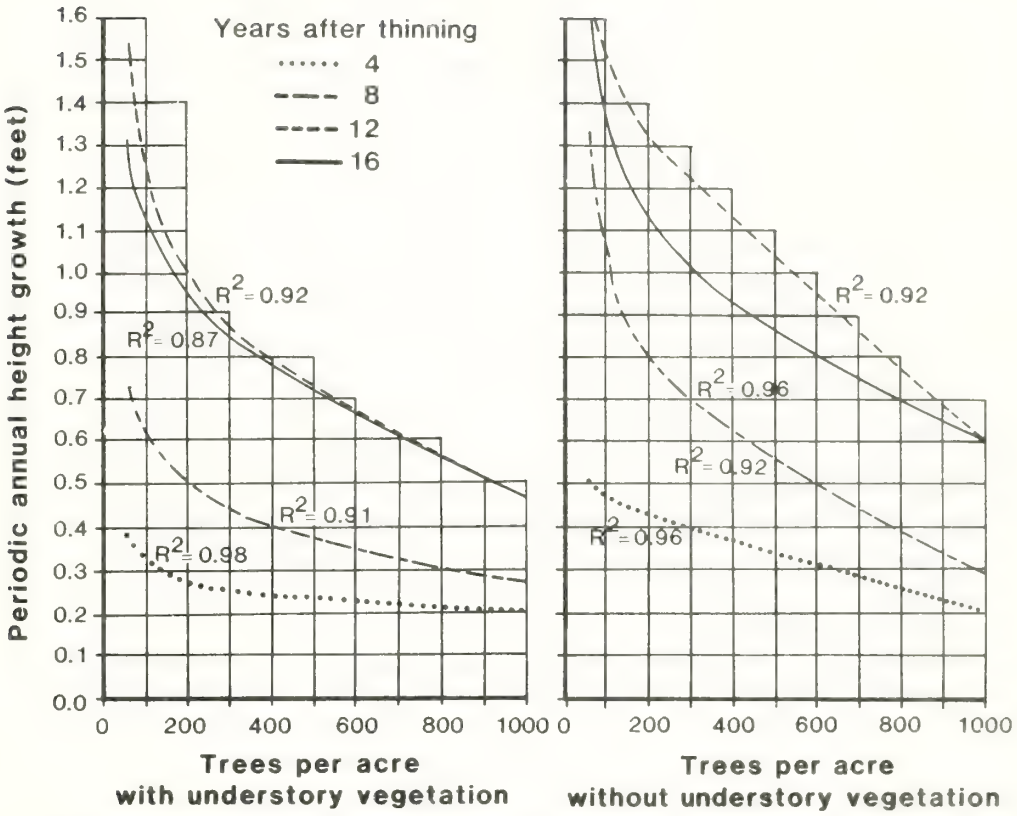

Figure 10.--Periodic annual height growth of thinned healthy ponderosa pine saplings (Barrett 1973). Brush was allowed to develop naturally on half the plots and was controlled on the other half.

Conclusion

Foresters should not be discouraged by the occasional resurgence of dwarf mistletoe in thinned, second-growth ponderosa pine because continued rapid height growth will produce healthy upper crowns free of mistletoe. The following field exercise is recommended to evaluate the growth of thinned sapling or small-pole stands infected by dwarf mistletoe.

1. Locate an adequate number (at least one per acre) of 1/20-acre circular plots (radius = 26.3 feet) within the stand.
2. Extract from each tree on the plot an increment core that includes as many rings before thinning as after thinning.
3. Measure and calculate growth rate per decade after thinning.
4. If time since thinning is less than 10 years, calculate a decadal rate. For example, if an increment core shows seven growing seasons since thinning and radial growth was 0.9 inch, decadal rate may be calculated as follows:

   $$\frac{0.9 \text{ inch}}{7 \text{ years}} = \frac{x}{10 \text{ years}},$$

   $7x = 9.0$,
   $x = 1.29$ inches radial growth per decade,
   $1.29 \times 2 = 2.58$ inches diameter growth per decade.
5. Calculate an average decadal growth rate per plot and compare this rate to that shown in figure 11. Growth rates should be at least 80 percent of the rate for the density indicated. Stands thinned 6 years or less should not be evaluated. Diameter growth rate can be useful in estimating the time needed before a commercial entry may be made and any badly infested trees harvested.
6. Adequate height growth—not diameter growth—is the key to productive growth in infested stands. In sampling growth of an infested stand, the most important fact to determine is whether or not most trees are attaining 10 inches or more of height growth annually.

If the sample plots reveal that stands are not growing at acceptable rates, and if numerous dwarf mistletoe plants appear in the upper one-fourth of the crowns on most of the trees, then serious consideration should be given to clearing the site and planting.

On the other hand, if growth rates approximate those in a healthy stand, the infested stand should be carried at least to a minimum merchantable size, at which time growth characteristics should be assessed again. If the stand, as a whole, continues to grow at acceptable rates, a commercial thinning could be made at merchantable age and the better trees retained to accumulate more volume and possibly act as a shelterwood for a new stand.

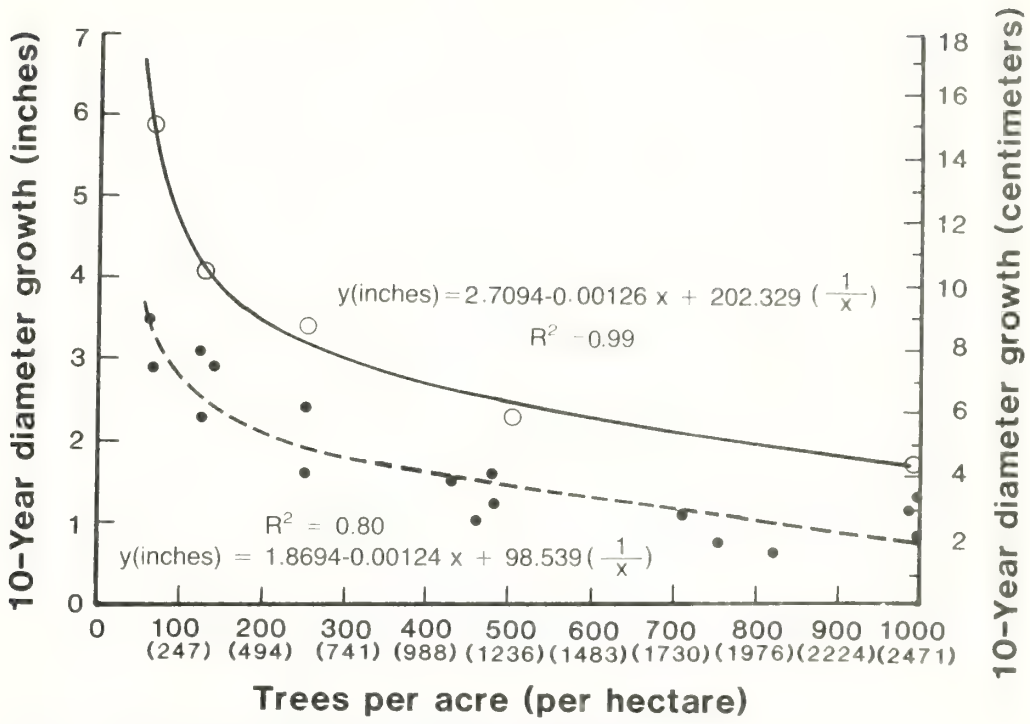

Figure 11.—Relation of diameter growth to density in suppressed, sapling-size ponderosa pine after thinning (Barrett 1979), with understory vegetation controlled, (solid line) and with understory vegetation allowed to develop naturally.

Metric Equivalents

1 inch = 2.54 centimeters
1 foot = 0.3048 meter
1 acre = 0.405 hectare
1 square foot/acre = 0.2296 square meter/hectare
1 cubic foot/acre = 0.06997 cubic meter/hectare
1 tree/acre = 2.471 trees/hectare

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Observations of thinned ponderosa pine infested with dwarf mistletoe over a 17-year period suggests that on average or better sites most infested stands can be managed to produce usable wood products in reasonable time, if trends found in juvenile stands continue.

Keywords: Thinning effects, western dwarf mistletoe, stand density, pre-commercial thinning, ponderosa pine, *Pinus ponderosa*.

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anuary 1985

Response of Dwarf Mistletoe-Infested Ponderosa Pine to Thinning:

2. Dwarf Mistletoe Propagation

Lewis F. Roth and James W. Barrett

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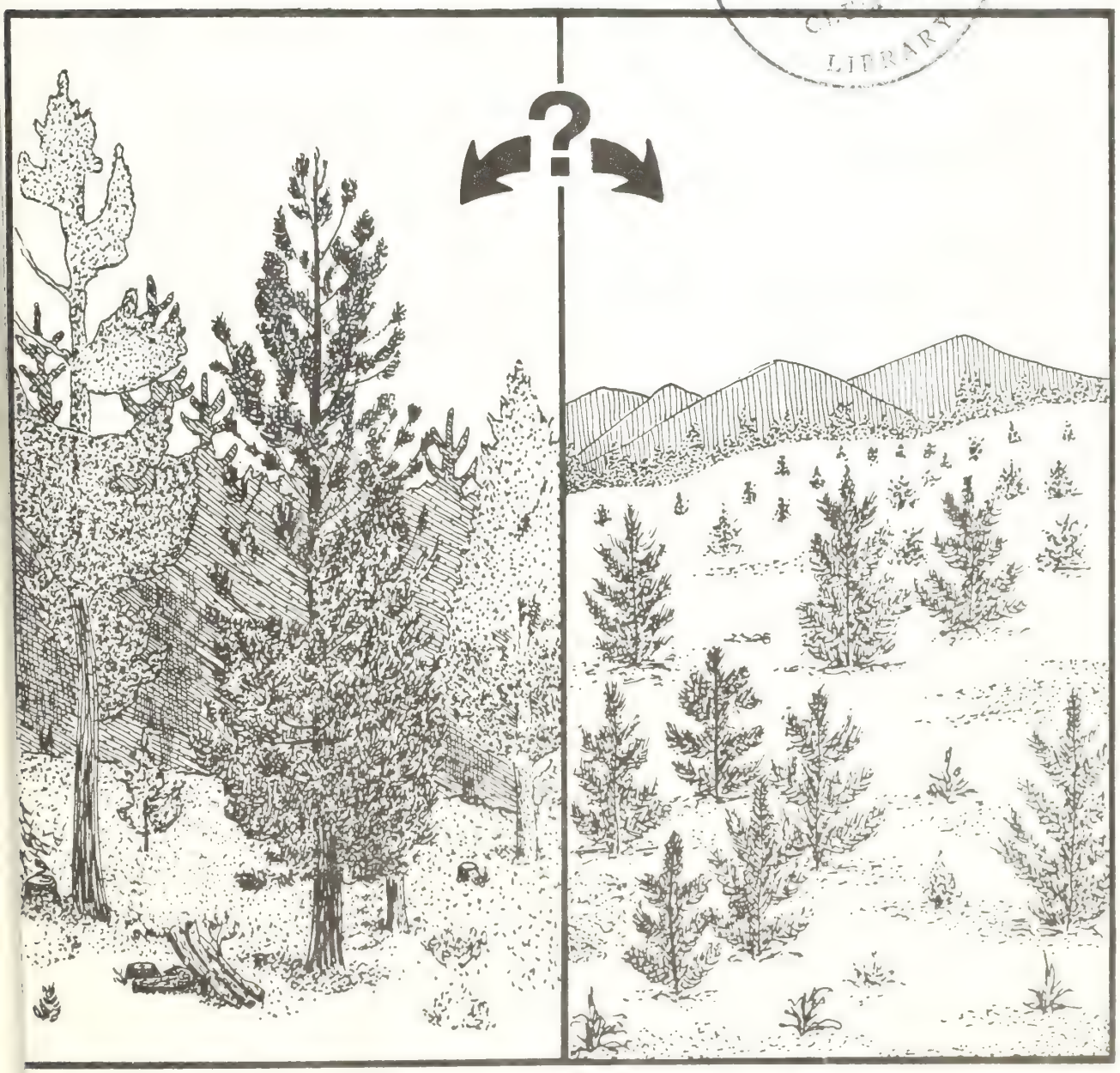

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Abstract

Roth, Lewis F.; Barrett, James W. Response of dwarf mistletoe-infested ponderosa pine to thinning: 2. Dwarf mistletoe propagation. Res. Pap. PNW-331. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 20 p.

Propagation of dwarf mistletoe in ponderosa pine saplings is little influenced by thinning overly dense stands to 250 trees per acre. Numerous plants that appear soon after thinning develop from formerly latent plants in the suppressed understory. Subsequently, dwarf mistletoe propagates nearly as fast as tree crowns enlarge but the rate differs widely among trees. The greatest increase is in the lower third of the tree crown. Parasite abundance had no measurable effect on height growth during 21 years following thinning, and height growth was faster than ascent of the parasite in the crown. Dominant trees that had 28 percent of crown length above the highest dwarf mistletoe plant in 1956 had 62 percent above in 1974.

Keywords: Thinning effects, parasites (plant), dwarf mistletoe, precommercial thinning, ponderosa pine, *Pinus ponderosa*, pathology (forest).

Research Summary

Population trends of western dwarf mistletoe were examined in 54 parasitized ponderosa pine saplings for 13 years, both before and after release of advanced regeneration by removal of the overstory and, without discriminating against trees with mistletoe, thinning the understory thickets to 250 trees per acre.

Before the stands were treated, the number of mistletoe plants increased at a slow, constant rate. After stand treatment, mistletoe propagated rapidly at varying rates. We were concerned about the effect of this rapid increase on crown development and tree growth. The variations in rate of increase resulted from removal of most of the stable seed source during stand treatment and from a flush of emergence and reproduction of previously latent plants that accompanied the excellent response of tree crowns to release.

Despite the conspicuous increase of mistletoe, the average number of plants per meter of stem decreased slowly with time after stand treatment. The decrease was marked on 19 trees, suggesting that they had substantial resistance to mistletoe. Tree crown density, but not height, increased rapidly immediately after stand release, trapping most of the mistletoe seed within the existing crown to establish new plants at the height of their parent plants, about 16 percent being in the upper crown. After height growth accelerated in the fifth or sixth year, proportionally fewer mistletoe plants established higher in the crowns. Only 1 percent of all plants were in the upper third of the crowns after 13 years. Observation four years later disclosed no plants in the upper third of the crowns of dominant trees. Dwarf mistletoe propagation relative to crown development was similar among dominant, codominant, and intermediate trees, suggesting that smaller trees can be safely kept for stocking purposes if they will truly respond to stand release. Suitability of parasitized pine stands for silvicultural treatment depends on whether trees will grow rapidly after release. Guidelines are given for identifying treatable stands and for selecting leave trees.

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ntroduction

On favorable sites, healthy advanced ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) regeneration that is protected from damage during overstory harvest responds quickly to release from competition and grows rapidly (Barrett 1970, 1973, 1979). Where western dwarf mistletoe (*Arceuthobium campylopodum* Engelm.) is abundant, however, many foresters question whether thinned stands will respond favorably. The negative view may lead to excessive clearcutting of infested stands, followed by uncertain, costly reforestation, or it may lead to rejecting any silvicultural treatment for potentially productive stands.

We know that dwarf mistletoe retards growth of unmanaged pine (Childs and Edgren 1967, Childs and Wilcox 1966, Shea 1964, Shea and Belluschi 1965, Weir 1916, Wilcox 1963) and extremely heavy infestations will stunt and kill trees (Roth 1971), but we are much less certain that managed stands suffer significantly.

This paper examines the dwarf mistletoe component of stand response where infested pine regeneration on the east slope of the Cascade Range has been released by thinning, following removal of the overstory.

Dwarf mistletoes, unlike the widely distributed microscopic fungal pathogens in the forest, scatter their seeds over short and definable distances, and plants that are reproductively mature are big enough to be easily seen. These features have encouraged foresters to undertake dwarf mistletoe control by harvesting the overstory and thinning to sanitize the understory (Hadfield and Russell 1978). Removal of the overstory is profitable, of course. Where appropriate, removal of parasitized understory trees can also be economically beneficial if it is integrated with thinning for stand improvement and enhanced growth (Barrett 1979, Sassaman and others 1977, Shea and Lewis 1971).

Early efforts to control dwarf mistletoe in advanced ponderosa pine regeneration were aimed at eradication (Childs 1963, Graham 1967, Shea and Lewis 1971). This objective tended to limit control to stands that had enough trees visibly free of dwarf mistletoe to adequately stock the site after treatment.

Contrary to expectations, dwarf mistletoe frequently recurred, even where all visible plants were removed. Resurgence resulted primarily from the emergence of previously undeveloped plants already established within the bark (Shea and Lewis 1971). In stands thinned to specified densities, the average stem diameter was also greatly reduced after treatment because dwarf mistletoe is most evident in the bigger trees (Childs 1963). Accordingly, foresters either backed away from managing infested stands or they destroyed them and replanted, thus incurring reforestation costs and sacrificing the contribution of accumulated growth toward shortening the timber rotation.

Following intensive examination of dwarf mistletoe in the diverse stands of ponderosa pine on the Pringle Falls Experimental Forest on the Deschutes National Forest in central Oregon, Roth (1952, 1953) suggested that pine might suffer little damage from dwarf mistletoe if growth conditions that allowed annual height growth exceeding 10 inches could be maintained. He further suggested that, on sites of good quality, recent height increment of the better trees, along with growth response to thinning, might be better criteria for guiding and evaluating

treatment than the amount of visible dwarf mistletoe. These suggestions helped prompt Barrett to establish the growth study (Barrett and Roth 1984) and guided the second thinning. This approach recognizes that after treatment most leave trees are parasitized. The amount of damage resulting from these plants is a valid concern and is examined here with respect to crown enlargement and height increment, the growth characteristics most reduced by dwarf mistletoe (Childs and Edgren 1967, Weir 1916).

When this study began, little was known about the effects of dwarf mistletoe on the growth of advanced pine regeneration. There was some difference of opinion as to whether the parasite was damaging at all. Nevertheless, abundantly parasitized, suppressed pines appear hardly to grow at all while lightly parasitized trees show no detectable reduction in growth. Between these extremes are intermediate frequencies of parasitism that damage physiological functions and must indirectly limit growth.

We understand very little of the process by which dwarf mistletoe actually damages trees. Although the parasite gets nearly all of its food from the tree, competition with the tree for nourishment seems moderate. Probably most important is disrupted translocation because the tree system, particularly the roots (Knutson and Toevs 1972), is deprived of the photosynthate formed distally to dwarf mistletoe plants (Leonard and Hull 1965, Rediske and Shea 1961). Disturbances of translocation also modify self-pruning of branches from the lower crown which may be delayed indefinitely. Such branches often distort to form brooms and, because of impaired translocation in the phloem, they contribute little to the tree's welfare. Like the parasite, they take valuable water and minerals. Such branches essentially become parasitic, and their demands—perhaps more than those of the parasite—contribute to the characteristic decline of the upper crown.

Tree growth is a direct function of crown size and photosynthesis (Grier and Waring 1974, Waring and others 1980). Consequently, we hypothesized that if crowns of infected saplings enlarge faster than the dwarf mistletoe propagates, the trees should grow productively. Since the resurgence of dwarf mistletoe is a common consequence of thinning we needed to know if it would nullify the growth benefits expected from thinning.

The Study

We examined dwarf mistletoe in crowns of advanced ponderosa pine regeneration with respect to increases in crown size and tree height. Data covered a 30-year period centered on the years 1957-58, when the experimental stand was released, then thinned to 250 trees per acre (Barrett and Roth 1985). In 1971 and 1972 when stocking was again reduced, from 250 to an average of 88 trees per acre, dwarf mistletoe plants were counted and annual increments of branchlet elongation measured by dissection of 26 intermediate, 12 codominant, and 2 dominant trees. This was more than a decade after initial thinning and long after formerly latent dwarf mistletoe plants had emerged.

Annual bud scars, which are recognizable for about 25 years back from branch tips, were used to identify points for branch dissection and determine age of dwarf mistletoe plants.

Twig growth for the previous 3 years was clipped from the tips of all branchlets and discarded as being too recent for dwarf mistletoe detection. Branches were then dissected at the bud scars and annual growth segments for all branches at each main-stem whorl were piled together by year of growth. Segments were scrutinized for dwarf mistletoe plants, measured, and their lengths totaled for each pile. Lengths for branches from all whorls were then totaled to describe each year's crown enlargement and to provide an index to crown mass. Dwarf mistletoe plants were recorded by year of origin of the supporting segment, branch whorl of their occurrence, sex, and size. This procedure included all but a few of the very oldest dwarf mistletoe plants that could not be accurately aged.

Length of the bole below the crown, length of each bole interwhorl, and length of leader were recorded. From the data a scale diagram was drafted of each tree enabling measurements of dwarf mistletoe plant locations relative to crown development and height growth (fig. 1).

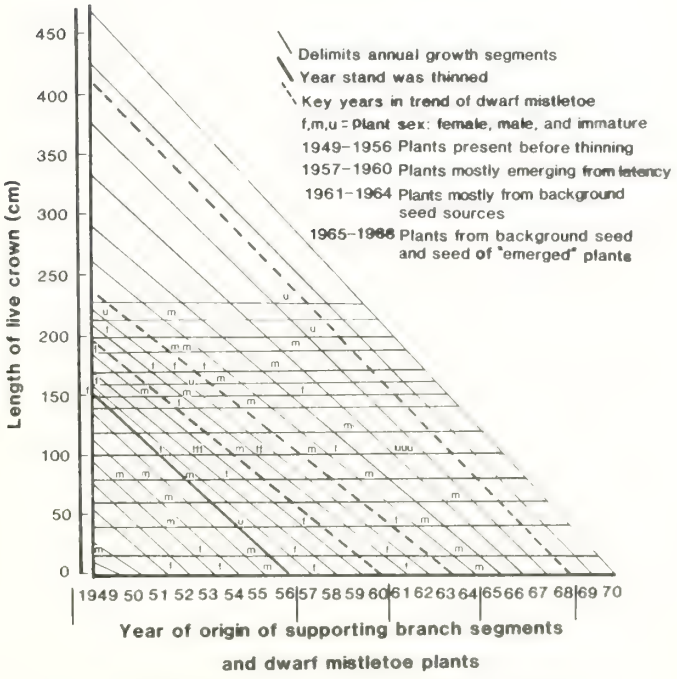
Delimits annual growth segments
Year stand was thinned
Key years in trend of dwarf mistletoe
f,m,u = Plant sex: female, male, and immature
1949–1956 Plants present before thinning
1957–1960 Plants mostly emerging from latency
1961–1964 Plants mostly from background seed sources
1965–1968 Plants from background seed and seed of "emerged" plants
Length of live crown (cm)
0
50
100
150
200
250
300
350
400
450
1949 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70
Year of origin of supporting branch segments
and dwarf mistletoe plants

Figure 1.—Diagram of the live crown of tree 9A showing location of dwarf mistletoe plants by position of supporting branch (horizontal lines) and year supporting branch segment originated (space between diagonal lines). The vertical axis only is drawn to scale. Diagrams of 54 such trees were used to measure population trends of dwarf mistletoe and ascent in crown relative to crown development. Because of branch inclination, some plants low in the crown were slightly lower and some high in the crown were slightly higher than shown.

Initially, we assumed that if the intermediate and codominant trees from the thinnings could enlarge their crowns faster than dwarf mistletoe increased, then certainly the same relationship would be true of the better trees in these classes and of the rapidly growing dominants. As the study progressed, however, the position of dwarf mistletoe plants within the crown relative to height growth appeared increasingly important. Consequently, in 1973 and 1974, we non-destructively sampled 14 standing trees, mostly dominants. Units identical to those on the dissected trees were measured.

The 54 trees measured were taken consecutively along three irregular traverses of the thinning plots (Barrett and Roth 1985).

Results

Effect of Thinning on the Number of Dwarf Mistletoe Plants

As crowns of the saplings slowly enlarged, the number of dwarf mistletoe plants gradually increased. Values in figure 2 for the period before 1957 represent infections existing, but mostly latent and invisible, during the decade preceding overstory removal and thinning, except for infrequent plants possibly arising on still susceptible 1954-57 wood. Because of the emergence of many plants from latency the pre-1957 values—as recorded in 1971—greatly exceed values that would have been recorded if data could have been taken before the stand responded to release. It seems especially significant, therefore, that the number of visible plants during the 4 years immediately following thinning doubled (fig. 2). Nearly all of this increase resulted from emergence of previously established plants because the source of seed to establish new plants was extremely depleted by the logging and thinning operations. Also, the interval of approximately 6-years between the first response to thinning and 1964 was too brief for abundant completion of the dwarf mistletoe life cycle to produce new plants from seed.

By 1961 the emergence response of dwarf mistletoe to thinning was substantially complete and growth from seed returned to a slower annual rate that would be expected in a vigorous managed stand (fig. 2, 1961-64).

This stable rate of increase was short lived; by 1965 the many latent plants that emerged after 1958 fruited prolifically after about 1961, initiating new populous generations.

Data in figure 2 are limited to 2 years of rapid increase. As in the preceding cycle, plant production should return to the slower (1961-64) rate in 3 or 4 years. Because of many unemerged juvenile plants on 1967 to 1970 wood, values beyond 1966 are partial. Had the study been extended plant numbers would have continued to rise after 1966.

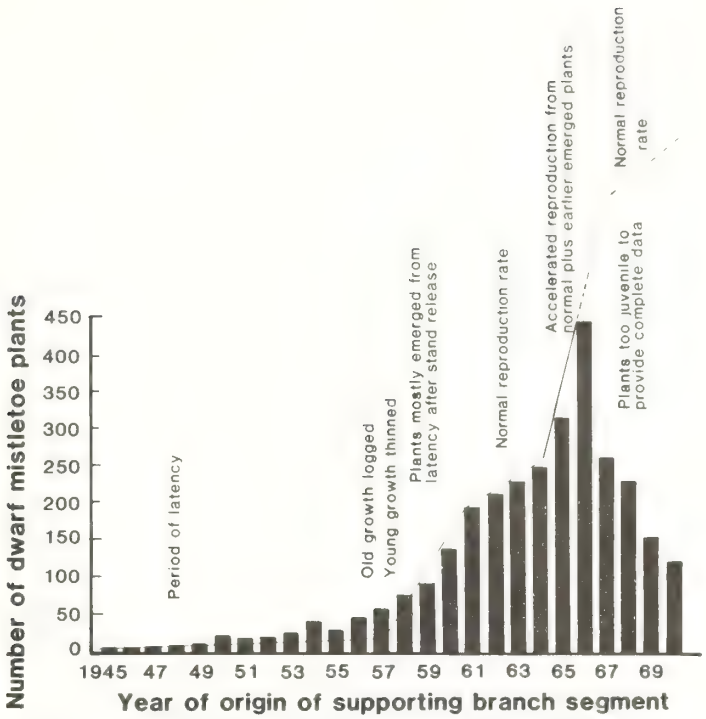

Figure 2.—Dwarf mistletoe population trends of 54 small, pole-size ponderosa pines: 14 dominants, 14 codominants, and 26 intermediates. Columns represent number of dwarf mistletoe plants originating on each successive year's shoots. Lines represent ascent rate variations of population development. Projection of bars preceding 1957 above line is an anomaly resulting from tabulation of formerly latent, invisible plants after they emerged in response to thinning.

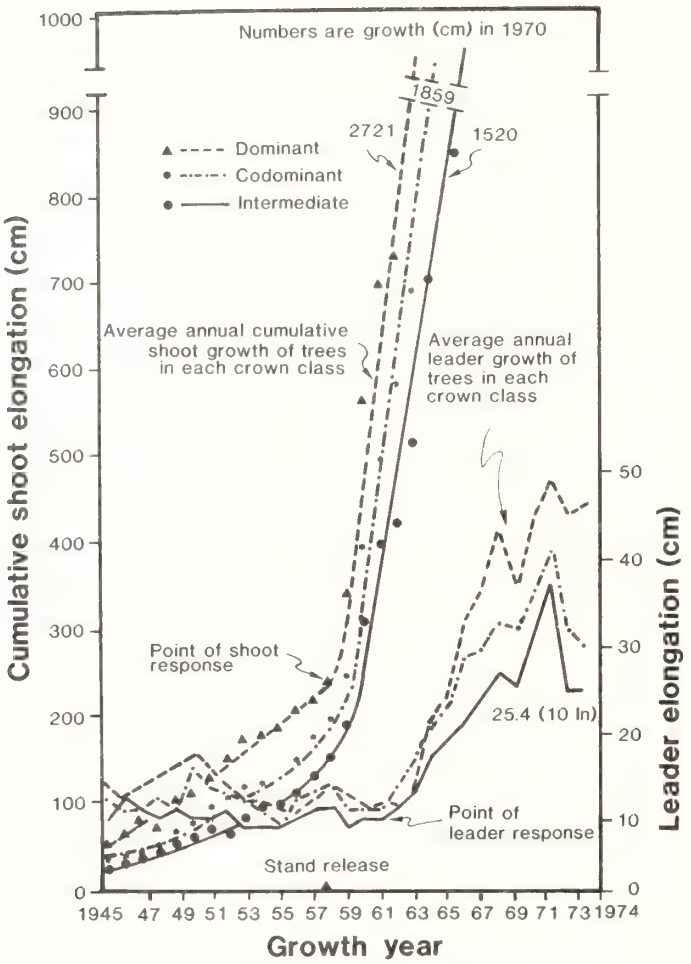

Figure 3.—Average annual shoot growth and leader elongation of 54 small, pole-size ponderosa pines. Dominants (14), codominants (14), and intermediates (26) are plotted separately. Annual leader length is graphed on data points. Visually smoothed curves are used for the annual sums of branch segment lengths.

Effect of Thinning on Crown Development and Ratio of Dwarf Mistletoe Plants to Crown Size

Crown development accelerated immediately following stand release in 1957-58 (fig. 3). Length and number of branchlets among the dominant trees quadrupled in the first growing season after thinning. The increase was even larger in subsequent seasons. During the 3 years following thinning, crowns of the intermediates enlarged nine times the pretreatment rate. An extremely rapid rate of crown enlargement was maintained by trees of all crown classes up to study termination in 1974. Height growth, notably, did not accelerate until 5 years after release (fig. 3). Trees retained in the growth study maintained an accelerated rate of crown enlargement through 1982 (Barrett and Roth 1985).

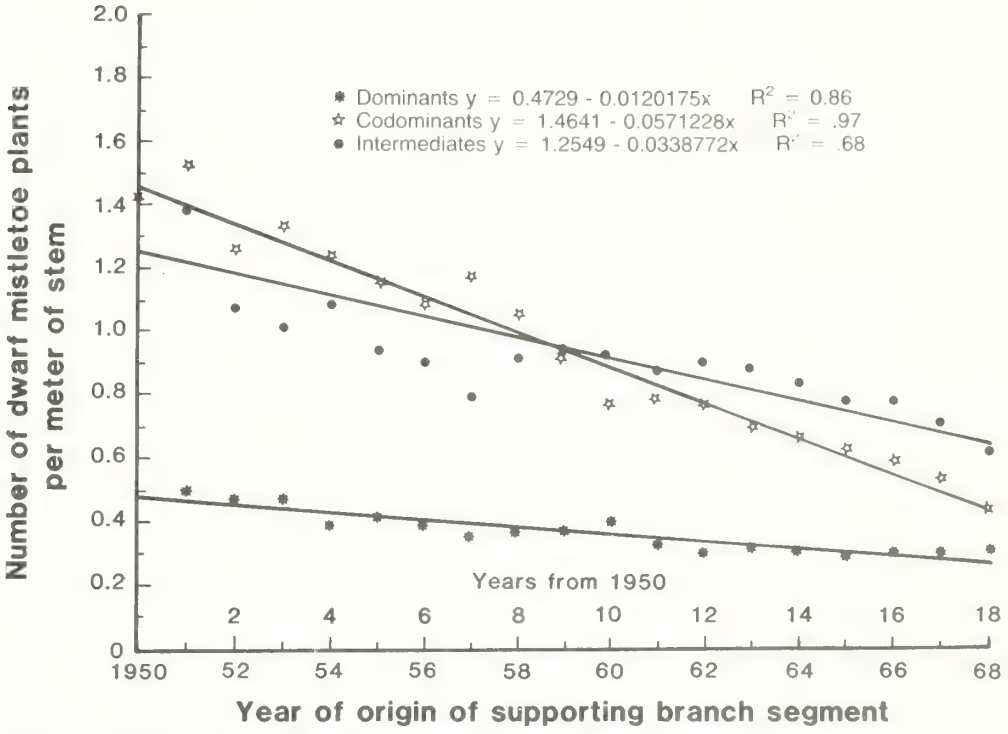
Number of dwarf mistletoe plants per meter of stem
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Dominants y = 0.4729 - 0.0120175x R² = 0.86
Codominants y = 1.4641 - 0.0571228x R² = .97
Intermediates y = 1.2549 - 0.0338772x R² = .68
Years from 1950
2 4 6 8 10 12 14 16 18
1950 52 54 56 58 60 62 64 66 68
Year of origin of supporting branch segment

Figure 4.—Number of dwarf mistletoe plants per meter of annual growth on branches comprising the crowns of 54 pole-size ponderosa pines. Dominants (14), codominants (14), and intermediates (26) are averaged separately and plotted.

Figure 4, covering the period 1950 to 1968, shows the relationship between the increase in dwarf mistletoe and crown enlargement, expressed as the number of dwarf mistletoe plants per meter of branch. Prior to 1950 crown enlargement averaged only 0.22 m of branchlet length per tree per year. On such slow growing trees data are highly variable and even one dwarf mistletoe plant greatly influences the plant to crown ratio. Data after 1968 underestimate the amount of mistletoe because of plant immaturity on the relatively new wood (fig. 2) and are excluded from figure 4.

The number of plants per unit of stem declined from 1950 to 1968 on trees in all crown classes. This decline was slow in the dominants, fairly rapid in the codominants, and somewhat variable in the intermediates. Only in the latter was there a suggestion that fewer plants per unit of stem resulted from stand release. If thinning had influenced the ratio, the slope of lines in figure 4 would have changed after thinning in 1957-58. These changes in plant to branch ratio indicate a consistent improvement in stand condition but are not particularly convincing evidence that the treated stands have overcome their dwarf mistletoe problem.

Between 1945 and 1970 the number of dwarf mistletoe plants per meter of stem increased on 20 of the 54 trees and decreased on 19. On fifteen there was no

change. A *t* test indicated that differences in height growth of trees with increasing and decreasing numbers of plants per meter during these 25 years were not significant ($P = .05$). At this early stage the amount of mistletoe was not influencing height growth.

In summary, while the number of dwarf mistletoe plants increased substantially after stand thinning, tree crowns enlarged correspondingly and the plant to crown ratio was little changed. The stand responded to thinning with growth equalling that of a thinned healthy stand (Barrett and Roth 1985). (fig. 3), and the amount of dwarf mistletoe had no detectable effect on tree height growth.

Location of Dwarf Mistletoe Plants in the Crown

The location of a dwarf mistletoe plant in the crown influences the plant's importance (Hawksworth 1961, Strand and Roth 1976). Because of their ability to disperse seed more widely, plants high in the crown are more threatening to the stand and perhaps more damaging to the host tree than are plants lower in the crown.

Understory trees that intercept seed from an infected overstory have limited opportunity to grow in height faster than the dwarf mistletoe establishes higher in the crown and commonly have plants relatively high in their crowns. In the absence of seed from the overstory, however, it appears that well spaced young pines can grow in height faster than the dwarf mistletoe can ascend. They may be able to do this even though dwarf mistletoe plants in understory crowns can throw seed higher than the tops of trees that bear them. The rate of dwarf mistletoe ascent depends on the height to which seed is thrown and on the probability that a given seed will establish an infection. This probability is very low (Strand and Roth 1976).

We hypothesized that sustained height growth of 10 or more inches (25.4 cm) a year would enable a tree to stay ahead of the dwarf mistletoe and would result in an increasingly larger proportion of the crown length above the mistletoe.

Tree growth is divided into the pre-thinning period of slow growth, extending from our oldest records in 1945 to 1957, and the post-thinning period of rapid crown enlargement from 1957 to 1974. The latter tree-growth period is divisible into four periods of recognizable dwarf mistletoe proliferation (fig. 2): 1957-61, when extensive emergence of latent plants combined with some normal regeneration from seed; 1961-64, when new plants arose almost entirely from seed; 1964-68, when plant regeneration from seed was excessive (the start of this period coincided with acceleration of tree height growth); and 1969-70, which was biologically similar to 1961-64 and ended with final dwarf mistletoe records from the dominant trees.

Foresters have found it useful to divide tree crowns horizontally into thirds based on equal divisions of the main stem within the crowns. Such division has biological significance as well, in that each crown part functions somewhat differently physiologically. The upper crown maintains height growth and position of the tree in the stand, the middle crown performs most of the photosynethesis and related functions, and the lower, senescent third contributes relatively little (Barrett 1968). Horizontal thirds, however, poorly represent the distribution of crown mass and, consequently, poorly reflect the size of the sections as targets for dwarf mistletoe seed. Despite this limitation, our data compare dwarf mistletoe distribution among crown thirds as of the end of the periods identified above.

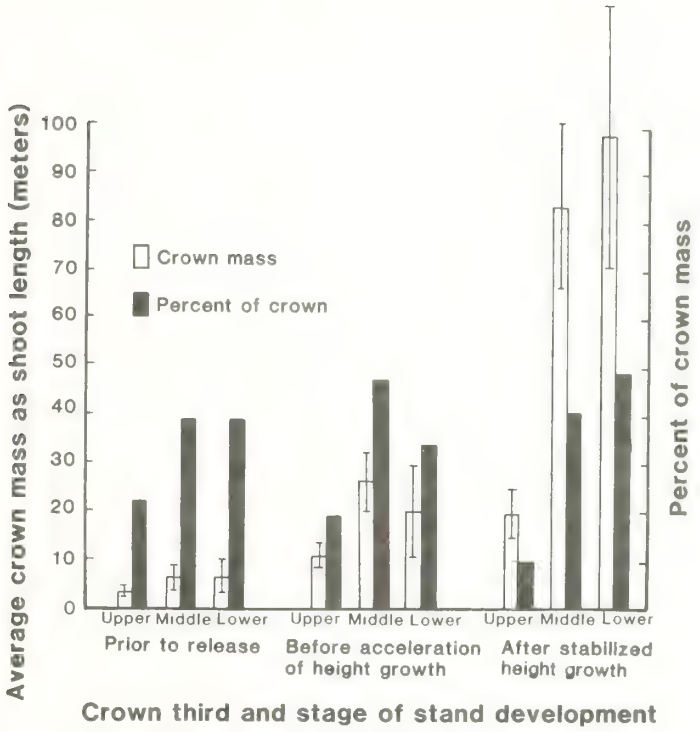

Figure 5.—Distribution of crown mass into horizontal thirds of the dominant trees at three stages of stand development: mass is represented as meters of shoot length (confidence limits P = .05).

Figure 5 shows distribution of crown mass of the dominant trees among crown thirds at the time of stand release, at the time of crown enlargement preceding accelerated height growth, and after rapid height growth stabilized.

The proportion of crown in the upper third of unreleased trees is larger than in released trees. This third, accordingly, is a proportionately larger target for dwarf mistletoe seeds. The upper crown third in fast-growing trees did not decline in relative size during the first 6 years after release and remained a comparatively large target, even though crown mass tripled. The proportion of mass in the middle crown increased somewhat during the 6 years following release but during the last period was similar to that in the first period. Consequently, there was a proportionate decrease in the upper crown, after initiation of accelerated height growth, and an increase in mass of the lower, less functional third of the crown. The distribution of dwarf mistletoe among crown thirds of the dominant, codominant, and intermediate crown classes was strikingly similar.

While the number of dwarf mistletoe plants quadrupled between 1956 and 1963, there was little change in the distribution of plants among crown thirds (fig. 6). This reflects the emergence of latent infections on old wood. New plants were similarly distributed among the enlarging crown thirds because crown configuration remained relatively unchanged during this time. After height growth accelerated in 1964, a marked and progressive difference developed in the distribution of plants among crown thirds. By 1970, 80 percent were in the lower third, and fewer than one percent were in the upper third, even though a 12-fold increase had occurred in the total number of plants. By 1974, with data available only for dominant trees, there were no plants in the upper crown third, and 87 percent were in the lower third.

The prevalence of dwarf mistletoe is frequently evaluated by a six point system (Hawksworth 1977, Hawksworth and Lusher 1956). If there are one or more dwarf mistletoe plants in a crown third, a point is recorded. If plants are on more than half the branches in a crown third (here corresponding to more than one plant on 3 m of branch) another point is added making possible a maximum total-crown rating of six points. Stands can be rated by adding values for individual trees and dividing the total by the number of trees.

Fourteen of our trees remaining after the second thinning were rated at significant times of stand and dwarf mistletoe development:

Period	Rating
1945-56	1.8
1957-60	2.3
1961-63	2.8
1964-68	2.8
1969-70	2.4

A sharp rise in rating (17 percent) occurred during the first years after thinning because latent plants emerged. This change was mostly from rating 1 to rating 2. Though sometimes conspicuous, this increase is scarcely real because most plants had been present but invisible at the first rating period. Ratings leveled off after 1961 (in spite of a great increase in total plants) until tree height growth accelerated in 1963, then ratings of all trees declined.

One tree rated 6 initially and five rated 5 or higher at intermediate periods. In 1970, however, none rated higher than 3. Since no dwarf mistletoe was found in upper crown thirds in 1974, the rating system probably overstates severity of the infestation. The nature of this overstatement is suggested by figure 7, which further relates location of dwarf mistletoe plants to crown development.

Uniformity of condition among the three crown classes is again striking (fig. 7). Through 1963 there was no detectable increase in the proportion of uninfected crown above the highest mistletoe plants. This distribution shows that directly after thinning growth of leaders was comparable to growth of other branches. There was no accompanying rise in height of the dwarf mistletoe plants because newly observed plants were primarily the latent infections emerging on old wood rather than new seedlings. By the time new plants from seed became numerous, height growth had accelerated faster than the ascent of dwarf mistletoe. So, by 1968, approximately the upper 45 percent of the crown length was above the highest dwarf mistletoe plants, and within 6 more years, 60 percent of crown length was above the highest plants.

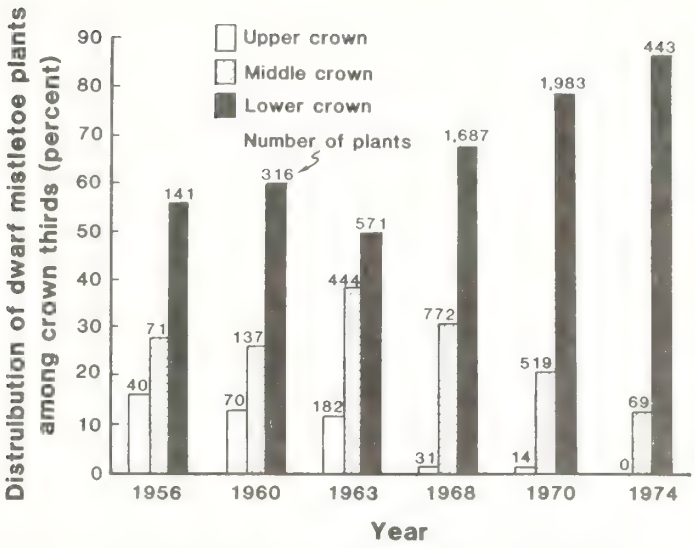

Figure 6.—Distribution, among crown thirds, of the total dwarf mistletoe plants (7,440) growing on 54 young ponderosa pines between 1945 and 1974. Plant numbers are reported just preceding stand release in 1956; when most latent dwarf mistletoe plants had emerged after stand release in 1960; immediately preceding accelerated leader elongation in 1963; when rapid leader growth had stabilized in 1968; and when data collection ended in 1970 and 1974. Data for 1974 describes dominants only. Dwarf mistletoe distribution was similar among crown classes.

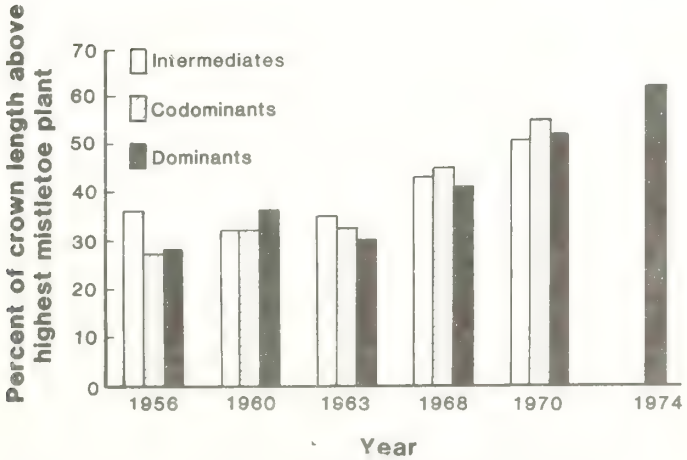

Figure 7.—Portion of crown length above the highest dwarf mistletoe plant in intermediate, codominant, and dominant trees at six key periods of stand and parasite development.

Discussion and Management Applications

The productivity of naturally regenerated, healthy ponderosa pine in the Pacific Northwest can be increased by releasing selected crop trees from competition. In the past, western dwarf mistletoe has caused various degrees of damage in much of the advanced pine regeneration. This has lead to divided opinion among foresters about the desirability of thinning infested stands.

Uncertainty about managing infested stands comes from past experience with both the poor appearance of unmanaged stands and the abundant dwarf mistletoe that recurs in managed stands. The history of control has shown regular resurgence. If the focus at decision time is on the abundance of dwarf mistletoe and accompanying tree distortion, destroying and replacing the stands will seem preferable to managing them. On the other hand, if the focus is on trees that are apparently clean and lightly parasitized, which are common in most infested stands on reasonably good sites, the decision is likely to be for stand management.

To provide a basis for making this decision we need to know how damaging the dwarf mistletoe that appears after treatment will be. Our study examined the assumption that infected trees would be productive in spite of the dwarf mistletoe, provided their crowns enlarged faster than the parasite reproduced.

To determine the ability of a tree to grow faster than its dwarf mistletoe, we annually compared number of dwarf mistletoe plants with crown mass. Mass was expressed as total length of all branches and branchlets. Data were from 40 recently felled intermediates and codominants encountered randomly along transects when the infected stand was reduced to 88 trees per acre after being thinned 14 years earlier to 250 trees per acre. Because of the lack of dominant trees in the thinnings, 12 standing dominants and 2 codominants encountered along the transects were also measured. All trees were parasitized by dwarf mistletoe, most of them for about 25 years.

Nearly all leave trees responded promptly to the first thinning. Needles increased in length and abundance. Needle color improved. Shoots proliferated and growth increased, paralleling changes in adjacent healthy stands thinned at the same time. Dwarf mistletoe also increased conspicuously. The response was similar in trees of all crown classes.

Except for the steady increase in crown mass after thinning, responses to release changed somewhat over time. The first change was the general increase in crown vigor just described. This change initiated a prompt, sustained increase in crown mass and a less prolonged increase in crown density. Crown shape remained unchanged for 5 or 6 years because all shoots, including the leader, elongate at roughly the same relative rate. We suspect that, during the first 5 years of good vigor, root development—which is distinctively poor in suppressed trees—occurred rapidly. After adequate roots developed, height growth accelerated, and crowns developed a more conical shape, with proportionately less mass in the upper third. There was no sign that this desirable growth trend would not continue through many decades.

Reproduction of dwarf mistletoe also changes with time. Within 4 years following stand release, plants appear on trees thought to be unparasitized and become conspicuous on recognizably parasitized trees. Since the main sources of dwarf mistletoe seed are removed by release cutting, plants that appear to be new are

those emerging from latency in response to increased host vigor. Some years are required for plants to become fruitful. Consequently, in the absence of a major seed source, the first flush of newly observed dwarf mistletoe is followed by approximately 4 years of rather stable populations. This period precedes a period of major population increase arising from seed produced by plants of the first flush. Stand treatment thus establishes a succession of small waves of dwarf mistletoe propagation, each about 10 years long and decreasing in depth, but not in number of plants.

Since the first wave of dwarf mistletoe plants grew mostly from seed in the former overstory, and because crowns remained somewhat rounded for several years after release, a higher proportion of the dwarf mistletoe population was in the upper third of the crown than will be likely in the future. When dwarf mistletoe is evaluated by the six point severity rating system during the decade in which the stand is released, a worsening condition is recorded over time. This is a misleading representation. During this period, number of plants and their distribution on the crop trees changes very little; only the appearance of the stand, resulting from emergence of long established dwarf mistletoe plants, is altered significantly.

From about the sixth year on, the pattern of dwarf mistletoe propagation is reversed. Newly appearing plants are new seedlings originating from seed produced within the stand rather than above it. They may quickly become abundant and fruitful but do not overcome their hosts for a number of reasons. Now seed dispersal is against gravity rather than with it. Susceptible branch tips are shielded by older needles from the dwarf mistletoe located within the crown. Trees are growing rapidly in height and forming new crown above the dwarf mistletoe, which is substantially screened in situ within the old hollow crown by dense shoots and foliage that developed right after thinning. And the old crown is rapidly becoming lower crown.

In 1956, 30 percent of the crown length of study trees was above the highest dwarf mistletoe plant, and by 1974 this had increased to 62 percent in the dominants, which then comprised most of the stand. During the 1956-74 period dwarf mistletoe progressed up the crown at the rate of less than 4 inches a year. The subsequent rate will be somewhat greater as propagation begins higher in the crowns where conditions are more open and consequently more favorable to the parasite. The six-point severity rating system reflects real rather than apparent conditions in the second and subsequent decades after thinning and should reliably indicate trends. On sites appropriate for management, ratings should progressively improve for at least several decades.

In trees of all crown classes we found that with passing time, there were fewer dwarf mistletoe plants, on the average, per unit of stem. The ratio of plants to stem increased, however, on 40 percent of the trees, suggesting that factors, such as differing inherent resistance, were influencing propagation rate within individual crowns. Trees with increasing numbers of plants per unit of stem grew in height at the same rate as trees with decreasing number of plants. Height growth exceeded 10 inches a year. While growth appeared unaffected by large amounts of dwarf mistletoe in stands thinned as lightly as 250 trees per acre, we concluded that highly susceptible trees, trees developing brooms, and trees not responding to the first thinning should be removed in a second thinning.

The favorable responses to thinning that we found should occur on suitable sites throughout the region. Additional study will provide refinements, but foresters need not await verification from plots in a particular region. Good height growth is the determining factor. If thinned, healthy stands in a particular locale will grow 10 inches or more a year (after the 5- to 6-year lag period) then infested stands should grow comparably.

Our results show that selected suppressed ponderosa pine saplings parasitized by dwarf mistletoe respond to release and grow productively. Proper selection of stands and trees is the key to most dwarf mistletoe management.

Extremely severe infestations of dwarf mistletoe in ponderosa pine occur on comparatively few acres of average or better sites in the Pacific Northwest. Such stands should be completely destroyed and regenerated.

Over most of the forest infested by dwarf mistletoe, control need not be the primary consideration. The main goal on both infested and clean sites should be acceleration of tree growth, which should handicap the parasite enough to enable the stand to complete a productive rotation.

In most of the ponderosa pine region, dwarf mistletoe can be reduced through the normal practices of timber stand improvement. The principal special requirements are: (1) the overstory, including all whips, be completely removed, (2) spacing be appropriate, and (3) the trees to be left be selected properly.

Correctly evaluated infested stands can be dealt with more or less as encountered. In the absence of fire, however, and with the probability that dwarf mistletoe damage will become more severe with time, there is reason to improve infested stands before healthy stands. Since our results show that managed infested stands can grow as well as clean stands for a long time after thinning, priority treatment of appropriate diseased stands is justified. Ordinarily the worst of the diseased stands that qualify for management should have first attention.

Identifying Manageable Stands

Certain stands can be summarily rejected. These are stands with densities below the minimum stocking level or that will fall below the minimum stocking curve after treatment (fig. 8); stands on scablands or other noncommercial forest sites; and stands that are hopelessly infested (all trees growing poorly and nearly all distorted).

Identifying pine stands that appear manageable can be aided by using the plant community guide appropriate to the area.

Eastern Oregon, Southeastern Washington	Hall (1973)
Central Oregon	Volland (1976)
South-central Oregon	Hopkins (1979a, 1979b)

Site index for different plant communities is estimated in these guides, as well as relative measures of productivity in cubic feet per acre per year. Sites that produce 20 cubic feet per acre per year or more qualify as commercial timberland.

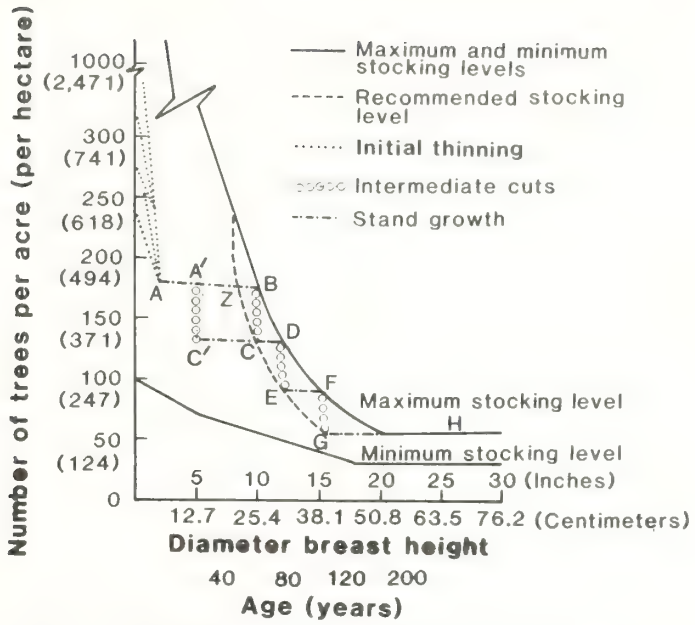

Figure 8.—Stocking level curves for healthy ponderosa pine where site index is IV or better (Barrett 1979, Meyer 1961) Optimum stand growth occurs between the recommended and maximum stocking level curves. In practice pine thickets are frequently noncommercially thinned to 180 trees per acre and an average stem diameter of approximately 2 inches or point A. Commercial tree harvests are made at points B, D, and F, and a final harvest of all trees somewhere along line H. Where dwarf mistletoe occurs, a second noncommercial thinning may be needed at point A' to remove undesirable trees to point C' before allowing the stand to grow to the maximum stocking level curve.

Since success in treating sapling stands infested by dwarf mistletoe depends largely on the ability of crop trees to grow well in height, only stands on land qualifying as commercial, with the potential of growing 10 or more inches a year, should be managed for timber production.

Determining capacity for height growth on average or poorer sites is difficult. Frequently, overstory trees have been harvested and the remaining advanced regeneration is suppressed in height, thus depriving the forester of a means for determining site index. Sometimes this dilemma can be avoided by measuring height growth for the last 5 years on advanced reproduction that is relatively free of competition. If growth of more open trees approaches 8 to 10 inches annually there is a good chance that, after thinning, crop trees selected from a dense stand also will show good growth. Hence, we can conclude that the stand is thinnable.

The next step is to determine that there are enough suitable leave trees to exceed the minimum stocking level. Where the general stand examination indicates that management is questionable because of abundant dwarf mistletoe, standards are needed for selecting leave trees.

For well stocked uniform sapling stands with or without overstories we recommend that the following categories be considered leave trees (in order of decreasing priority):

1. Unparasitized dominants and codominants.
2. Dominants and codominants with dwarf mistletoe in only the lower third of the crown.
3. Dominants and codominants with dwarf mistletoe in only the lower half of the crown.
4. Dominants and codominants with dwarf mistletoe in only the lower two-thirds of the crown.
5. Intermediates with no visible dwarf mistletoe.
6. Intermediates with dwarf mistletoe only in the lower third of the crown, or, if a tree is required for spacing, in the lower half of the crown.
7. Trees below the general canopy having high vigor, good crowns, and no dwarf mistletoe.

A crop tree should not have dwarf mistletoe on more than half the branches of any designated portion, and there should be no plants on or within 8 inches of the main stem.

Selected trees must show potential for good height growth as evidenced by a good crown and a single vertical leader that has grown well in the previous 5 years.

Stands of trees that meet the above requirements should be thinned. Small patches of qualifying trees in extensive areas of nonqualifying trees should be destroyed and regenerated along with the rest of the area—unless this conflicts with other resource management objectives.

Lightly Stocked Stands of Larger Trees

It is difficult to evaluate infested, lightly stocked stands of larger trees distributed unevenly in patches of different densities. When stocking is light, parts of the stand will be open or brushy (consult the minimum stocking level curves in Barrett 1979). If brooming is absent, dwarf mistletoe may appear less damaging than in dense stands. Growth response to thinning will be less, however, and there is no certainty that height growth will exceed 10 inches after thinning. Thinning will result in additional unproductive open space, and stands will overcome the dwarf mistletoe slowly, if at all. Brush control may stimulate adequate height growth of such stands on average sites. Sparse, uneven, infected stands, or those on below-average sites, probably should be destroyed and regenerated.

Stands of very uneven height that include infected pole-size trees are especially hard to evaluate because they have overstory/understory relationships that favor the spread of dwarf mistletoe. Diversity of size introduces the complexity of timeliness for treating such stands. Evaluating the timing of treatment involves considering stand structure, dwarf mistletoe propagation, and economics that are beyond the scope of this paper, but have been considered by Graham (1967).

Treatment of Infested Stands

Suggestions for laying out dwarf mistletoe control units to reduce perimeters, establish optimum boundaries, and achieve other desirable features are discussed by Childs (1963), Graham (1967), and Weir (1977).

Stands should be thinned to the desired level of stocking, leaving the best trees, as identified by criteria used above in examining stands for manageability. Even thoughtful application of the best procedures for selecting leave trees cannot assure that all trees will respond. Where economics will allow, thinning in two stages or follow-up cutting in 6 to 10 years is best.

While data for this paper are based on 250 trees per acre, reducing to 180 trees initially (fig. 8) will allow for later removal of trees that fail to respond to release and parasitized trees that are exceptionally damaged after thinning. Though the delay is not recommended, the second entry can be postponed until the earliest possible commercial thinning.

Pruning Considerations

Removal of heavily parasitized branches by pruning can have desirable, long-term effects. Dwarf mistletoe plants throw seed vertically for several feet and past a number of branch whorls, the distance being greater where crowns are more open. Strand and Roth (1976) found, however, that most seeds probably will not establish new plants. Moreover, once a seed is effectively placed to establish a new plant, there will be no further spread from that seed for about 6 years because of the extended dwarf mistletoe life cycle. Consequently, the rate of dwarf mistletoe ascent in the crown is slow and is directly related to the vertical distance between branches.

There is no certainty that the advantage gained by a tree over dwarf mistletoe, as a result of thinning while plants are mostly in the compact lower crown, will continue indefinitely. The facts that height growth of ponderosa pines slows again in later life and that dwarf mistletoe spreads faster in the more open crown portions (Barrett and Roth 1985). than in dense lower crowns suggest that the race between tree height growth and the upward movement of the parasite in the crown will narrow before stands reach rotation age. If changes in the crown that favor faster ascent of mistletoe are large, considerable damage can result. Much of the increase in mistletoe could be avoided by pruning the heavily parasitized dense lower crowns 10 to 15 years after thinning, before the parasite begins to propagate actively in the elongating upper crowns.

Pruning also would reduce opportunities for the formation of brooms and the damaging physiological effects mentioned earlier. It would further enhance timber quality by limiting development of large knots.

Metric Equivalents

1 centimeter = 0.3937 inches
1 meter = 3.281 feet
1 cubic meter = 35.32 cubic feet
1 hectare = 2.471 acres
1 tree/hectare = 0.4047 trees/acre

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Keywords: Thinning effects, parasites (plant), dwarf mistletoe, precommercial thinning, ponderosa pine, *Pinus ponderosa*, pathology (forest)

Propagation of dwarf mistletoe in ponderosa pine saplings is little influenced by thinning overly dense stands to 250 trees per acre. Numerous plants that appear soon after thinning develop from formerly latent plants in the suppressed understory. Subsequently, dwarf mistletoe propagates nearly as fast as tree crowns enlarge but the rate differs widely among trees. The greatest increase is in the lower third of the tree crown. Parasite abundance had no measurable effect on height growth during 21 years following thinning, and height growth was faster than ascent of the parasite in the crown. Dominant trees that had 28 percent of crown length above the highest dwarf mistletoe plant in 1956 had 62 percent above in 1974.

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Experiment Station

Research Paper
PNW-332

January 1985

GEORGIA'S Forest Products Industry: Performance and Contribution to the State's Economy, 1970 to 1980

Wilbur R. Maki, Con H Schallau, Bennett B. Foster, and Clair H. Redmond

Abbreviations

States

AL Alabama
AR Arkansas
FL Florida
GA Georgia
KY Kentucky
LA Louisiana
MS Mississippi
NC North Carolina
OK Oklahoma
SC South Carolina
TN Tennessee
TX Texas
VA Virginia
SO South
US United States

Industries

FPI Forest Products Industry
LWP Lumber and Wood Products
PAP Paper and Allied Products
WF Wood Furniture

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Abstract

Maki, Wilbur R.; Schallau, Con H; Foster, Bennett B.; Redmond, Clair H. Georgia's forest products industry: performance and contribution to the state's economy, 1970 to 1980. Res. Pap. PNW-332. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 22 p.

Employment and earnings in Georgia's forest products industry, like those of most Southern States, grew significantly between 1970 and 1980. The forest products industry accounted for nearly the same share of the State's economic base in 1980 as in 1970. Moreover, during this period, the State increased its share of the Nation's forest products industry employment and earnings. Pulp and allied products had the highest productivity, but lumber and wood products experienced the largest increase in productivity between 1972 and 1977.

Keywords: Forest products industries, economics in wood industry, Georgia.

Preface

Georgia's forest products industry, like that of most Southern States, experienced significant growth during the 1970's. This resurgence resulted from the increasing size and amount of timber, investment in new plants and equipment, and a growing demand for Georgia's forest products.

This report briefly describes Georgia's forest products industry--its composition, location, evolution, and relation to economic activity elsewhere in the State, the South, and the Nation.

This is one in a series of reports for each of the 13 Southern States. These reports are companions to a forthcoming analysis of the changing roles of the forest products industries of the South and the Pacific Northwest.

Highlights

- In 1980, the forest products industry was the fourth largest component of Georgia's economic base (the economic base is comprised of industries producing for export outside the State). Furthermore, the forest products industry accounted for as large a share of the State's economic base in 1980 as in 1970.

- Paper and allied products manufacturing is the largest component of the State's forest products industry. During the 1970's, it was the fastest growing segment of Georgia's forest products industry in terms of both employment and earnings.

- Pulp and allied product manufacturing accounted for the largest share of value added by Georgia's forest products industry. Lumber and wood products, however, showed a significantly greater increase in the rate of growth between 1972 and 1977.

- In terms of capital productivity (measured in terms of value added minus payroll, per worker hour), Georgia's forest products industry was the third most efficient in the South.

- In 1977, paper and allied products had the highest productivity in the State's forest products industry. Lumber and wood products, however, exhibited the greatest increase in productivity between 1972 and 1977.

- During the 1970's, Georgia increased its share of the Nation's employment and earnings in the forest products industry.

- In 1980, average earnings in Georgia were below the average for the Nation's forest products industry. But between 1970 and 1980, the rate of growth in earnings in Georgia exceeded the rate for the Nation.

- Earnings for Georgia's paper and allied products workers were significantly greater than the earnings in the other segments of the forest products industry.

- In 1980, only five Southern States were more dependent on the forest products industry than was Georgia.

- In 1977, the forest products industry in Georgia produced more value added than did its counterparts in all other Southern States except North Carolina.

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ne Forest Products conomy of Georgia

e State's Workforce

Georgia's estimated full- and part-time workforce in 1980 was comprised of an estimated 2.6 million employees and proprietors (see appendix tables for sources of employment and earnings data). Like most Sun Belt States, Georgia's workforce grew faster between 1970 and 1980 than did the national average (28.1 percent versus 22.3 percent). Total earnings--wage and salary payments and proprietorial income--also grew faster than the national average. Measured in constant 1977 dollars, the State's earnings increased by 37.2 percent as compared to 27.4 percent for the Nation. As can be seen in the following tabulation, manufacturing, services, and state and local government were the State's three largest employer categories:

	Percent of total employment, 1980	
Employers	**Georgia**	**U.S.**
Major industries:		
Manufacturing (including the forest products industry)	19.94	19.15
Services	15.92	18.22
State and local government	13.34	12.56
Retail trade	13.19	14.18
Transportation, communication, and public utilities	5.45	4.84
Wholesale trade	6.09	4.97
Nonfarm proprietors	5.97	6.58
Agriculture	4.25	4.39
Construction	4.04	4.08
Subtotal	88.19	88.97
All other industries	11.81	11.03
Total	100.00	100.00

Components of the State's Economic Base

Along with total employment, there is another and perhaps more important way to judge an industry's contribution to Georgia's economy. For the State's economy to grow and develop, it must attract "new dollars" so residents can buy goods and services produced elsewhere. The industries that export products and services to other states and the world and bring in new dollars constitute the State's "economic base." Generally speaking, most manufacturing employment is classified as "economic base" (or "basic"), while service or "residentiary" employment (for example, barber shops, realty firms, schools, and local government) is primarily geared to producing for local needs.

Residentiary employment is supported by the economic base. Money flowing in provides income for wage earners and entrepreneurs to spend on locally purchased goods and services. In most cases, the economic growth of a region is dependent upon the success of its economic base.

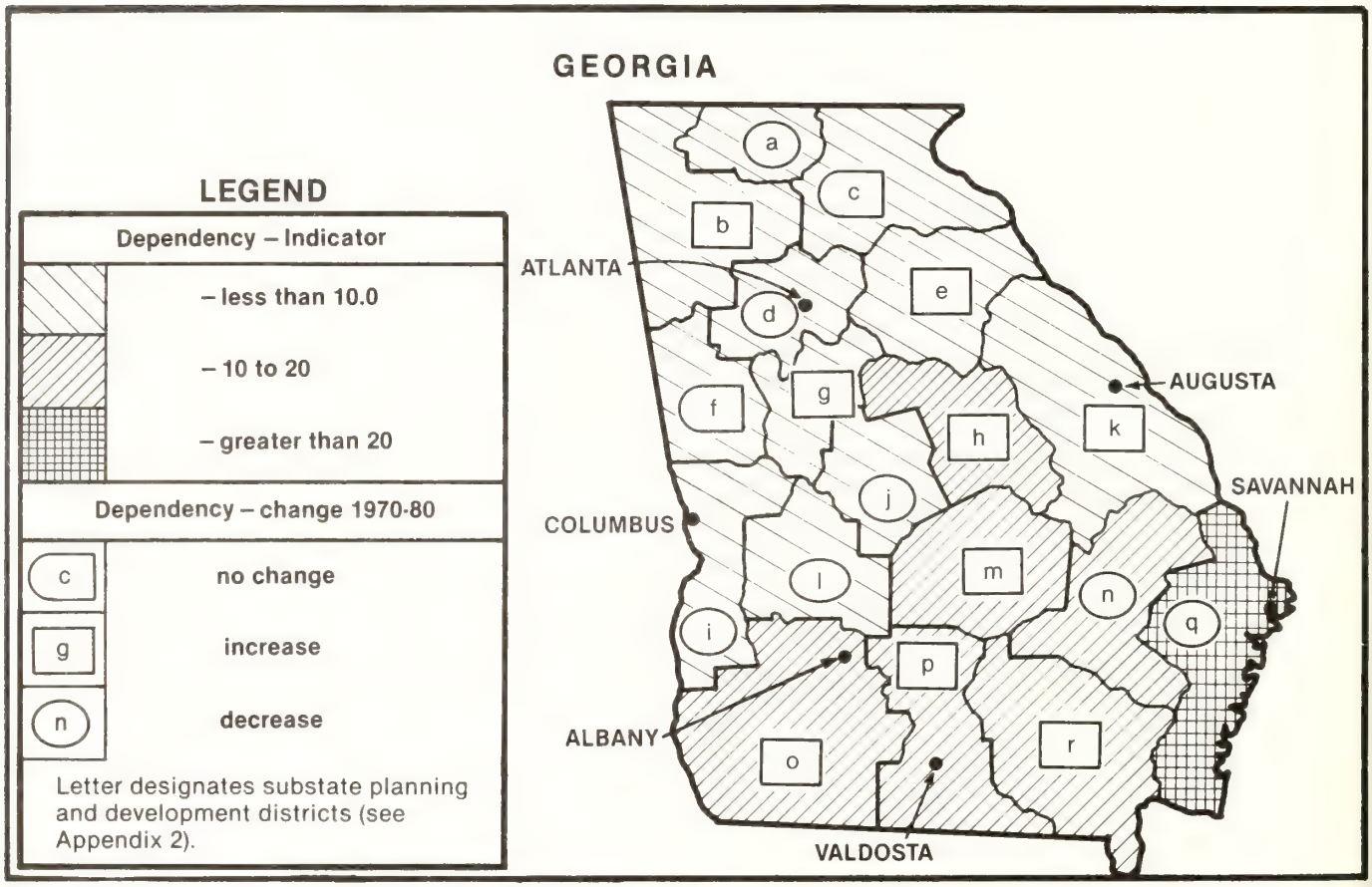
We used the "excess employment" technique to identify the industries that comprise Georgia's economic base. This approach accepts the national distribution of employment among industries as a norm. Any industry with employment in excess of this norm is considered to be producing for export markets outside the State and is part of Georgia's economic base. The percentage of Georgia's excess employment served as an indicator of the State's dependency on a particular industry for generating new dollars from outside the State. The percentage associated with the forest products industry is defined as the **timber-dependency indicator** (table 2 describes how excess employment and industry dependency indicators for Georgia were calculated).

In 1980, ten industries accounted for nearly 96 percent of the State's "excess employment"-that is, its economic base (see tabulation below). Though these same industries accounted for only a slightly smaller share (95.06 percent) in 1970, the change in shares of certain individual industries was quite significant. Textiles and apparel dominated Georgia's economic base, but less so in 1980 than in 1970. Federal military and civilian employment was also less important in 1980 than 1970. the growth of Georgia's transportation industry reflects the importance of Atlanta as a major air transportation center. As seen in the following tabulation of selected industry dependency indicators, the forest products industry was nearly as important in 1980 as in 1970.

Economic base industries	Dependency indicator	
	1970	1980
	(Percent of economic base)	
Textiles and apparel	48.53	44.92
Wholesale trade	4.67	10.43
Federal military	14.82	10.06
Forest products	7.63	7.09
Transportation	3.88	6.93
Food and kindred products	4.42	5.91
Federal civilian	5.92	4.23
Agriculture	3.28	4.15
Nonmetallic minerals	1.50	1.49
Services	.64	1.18
Subtotal	94.29	96.39
All other industries	5.71	3.61
Total	100.00	100.00

Geographical Importance of the State's Forest Products Industry

The contribution of the forest products industry to Georgia's economic base varies considerably between substate districts (see Appendix 2 for a listing of counties by district). Generally speaking, the forest products industry is more important in southern Georgia than elsewhere. For example, the forest products industry accounts for 25 percent of the economic base (that is, those industries producing for export to other states and the rest of the world) in the Savannah area, but less than 1 percent in the Atlanta area. Georgia's dependency on the forest products industry to produce exports increased in most substate districts between 1970 and 1980. An important exception was the Savannah area, where it decreased slightly.

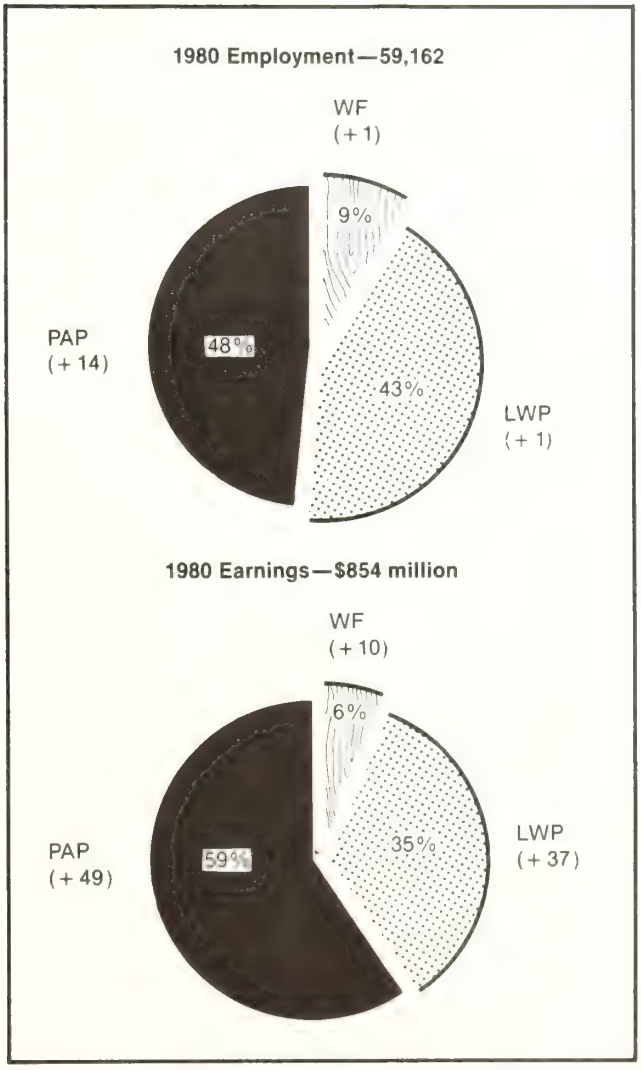


Source: Substate estimates for 1970 and 1980 were derived from unpublished county data series provided by the U.S. Department of Commerce, Regional Economic Information System, Washington, DC; and from the Department's *County Business Patterns*. The lower case letters used to designate substate districts correspond to the geographical classification of counties as shown in Appendix 2.

Composition of the State's Forest Products Industry

Georgia's forest products industry is comprised of paper and allied products, lumber and wood products (not including mobile homes), and wood furniture manufacturing. In 1980, paper and allied products accounted for the largest share of approximately 59,000 workers employed by Georgia's forest products industry. This industry also had the largest share of 1980 earnings.

Wood furniture and lumber and wood products employment changed little during the 1970's. Growth in employment of paper and allied products was substantially greater than for the other two components. Employment in all three forest products industries grew less rapidly than did the average for all industries (22.3 percent). Growth of wood furniture earnings lagged behind the national average (27.4 percent), although earnings growth for the other components exceeded the national average.

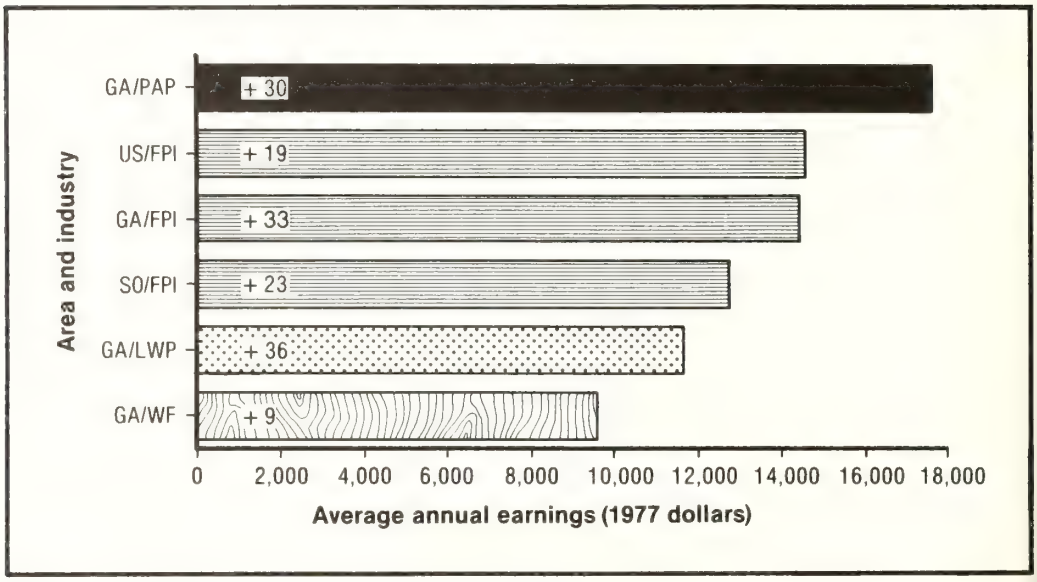


Numbers in parentheses show percent of change from 1970 to 1980.

Average Annual Earnings per Worker

Average annual 1980 earnings per worker in paper and allied products were significantly greater than were earnings in the other two forest products industries. Higher average skill levels and capital per worker, and unions account for this difference. Earnings in the wood furniture industry were half those for paper and allied products and significantly below the average for all forest products industries in the South and the United States.

Average annual earnings in Georgia were nearly equal to the average for the Nation's forest products industry; moreover, average growth in earnings was greater for Georgia than for the Nation. Growth of earnings for the wood furniture industry lagged behind the rest of the industry.

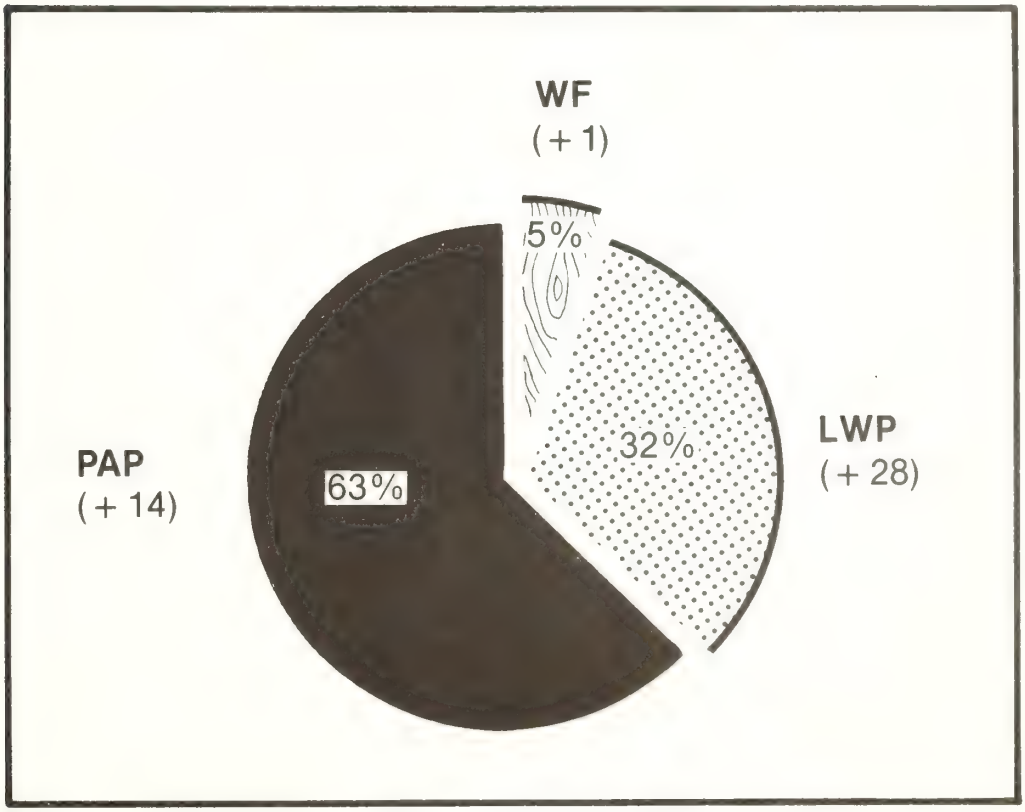


Numbers in bars show percent of change from 1970 to 1980.

Value Added by the Forest Products Industry

Value added by manufacturing represents income payments directly to workers and business owners. It is equal to the value of shipments less the cost of materials, parts, supplies, fuel, goods purchased for resale, electric energy, and contract work. Unlike value of shipments, value added avoids double counting. Consequently, value added by manufacturing is considered the best monetary gauge of the relative economic importance of a manufacturing industry.

In 1977, paper and allied products accounted for more than half of the $1.5 billion of the value added by Georgia's forest products industry. But between 1972 and 1977, the value added by lumber and wood products grew at twice that of paper and allied products.

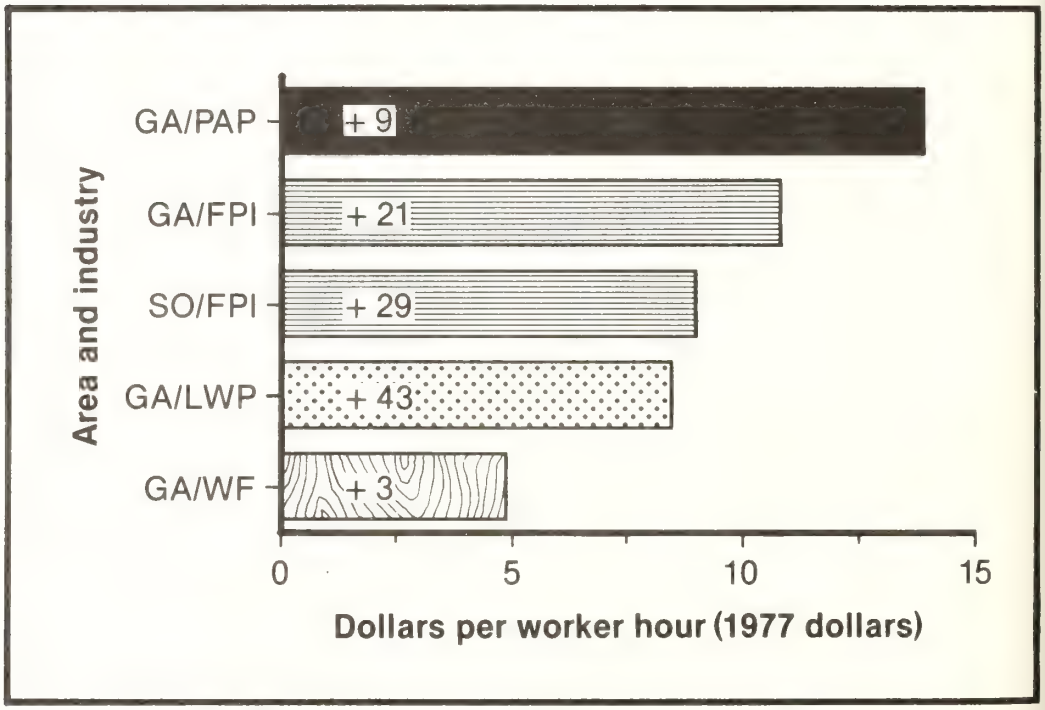


Numbers in parentheses show percent of change from 1972 to 1977.

Capital Productivity

Increases in productivity are necessary for an industry to remain competitive in the marketplace. Capital productivity of an industry is measured in terms of value added less payrolls per worker hour--VAMP (see table 3 for an explanation of how capital productivity was calculated for Georgia's forest products industry). This measure of productivity adjusts for wide differences in payroll among industries and represents the return to capital investment and entrepreneurship.

Not surprisingly, paper and allied products had the highest productivity in Georgia's forest products industry. This industry is more capital intensive and in the past has attracted considerable investment in new facilities and equipment. During the mid-1970's, however, the lumber and wood products industry exhibited a larger gain in productivity than did paper and allied products. Continued improvements in logging techniques and the growth of plywood manufacturing accounted for most of the gain in the lumber and wood products industry. The relatively low productivity of the wood furniture industry as compared to the rest of the forest products industry reflects the labor intensive nature of its manufacturing process.

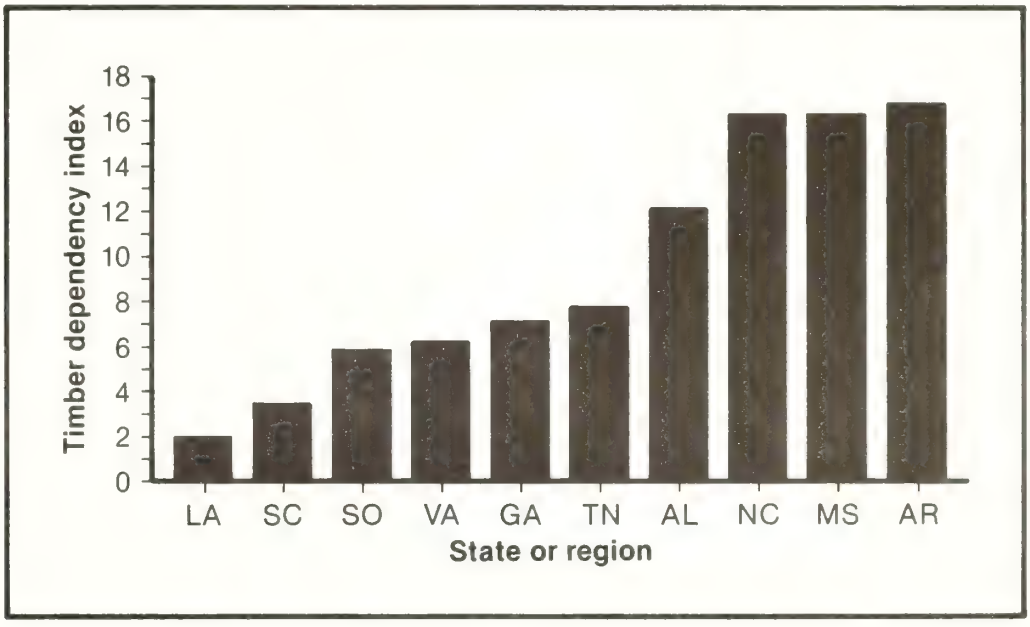


Numbers in bars show percent of change from 1972 to 1977.

The Forest Products Industry in the South

Importance of the Industry Across the South

The dependency indicators suggest that all but four States in the South manufacture forest products in excess of local needs: Florida, Kentucky, Oklahoma, and Texas were not self-sufficient with respect to forest products. Consequently, on net balance, their respective forest products industries did not generate new dollars from outside. In Georgia, the forest products industry accounts for 7.1 percent of economic base employment, or approximately 1 out of 14 basic employees. In three states--North Carolina, Arkansas and Mississippi--the forest products industry accounted for approximately 16 percent of those State's economic base, or 1 out of 6 basic employees.



Industry Composition

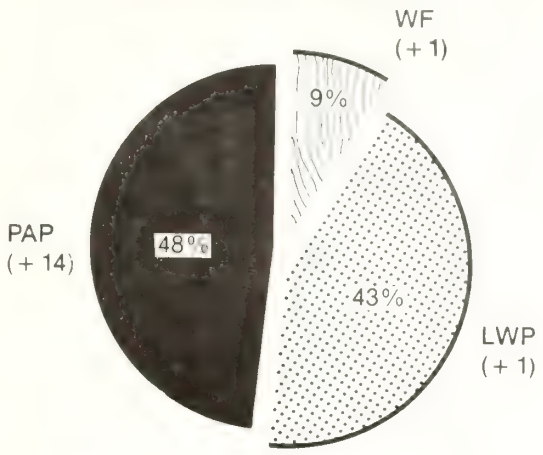
Paper and allied products accounted for a larger share of Georgia's 1980 forest products industry employment and earnings than it did for either the South or the Nation. Although this industry's employment increased in Georgia and the South between 1970 and 1980, it decreased nationwide. Likewise, the growth of the paper and allied products industry's earnings nationwide lagged behind those in Georgia and the South.

The wood furniture industry is a less important segment of the forest products industry in Georgia than in the South or the Nation. Furthermore, growth of this industry's employment and earnings were greater for the South than for Georgia.

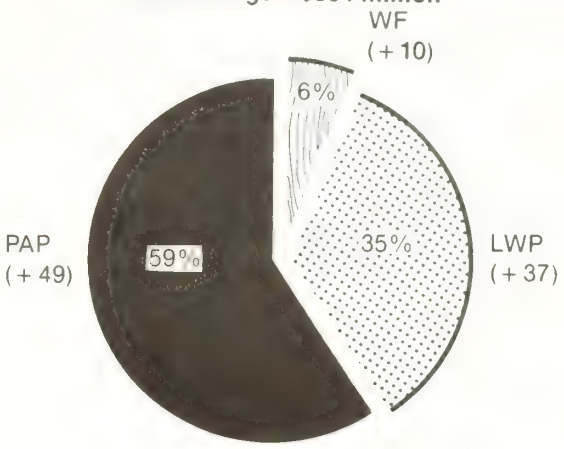
Lumber and wood products accounted for about the same proportion of Georgia's forest products industry as it did for the South and the Nation. During the 1970's, employment growth in Georgia was less than elsewhere. Growth in earnings was greater, however, in Georgia.

GEORGIA

1980 Employment—59,162

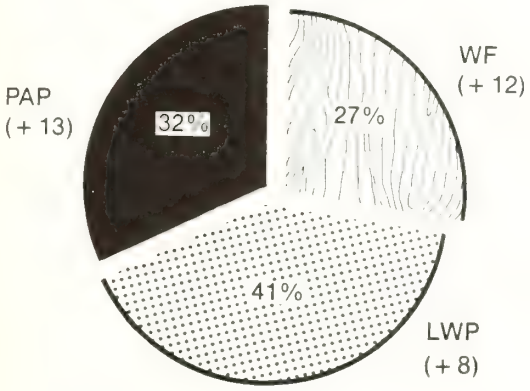


1980 Earnings—$854 million

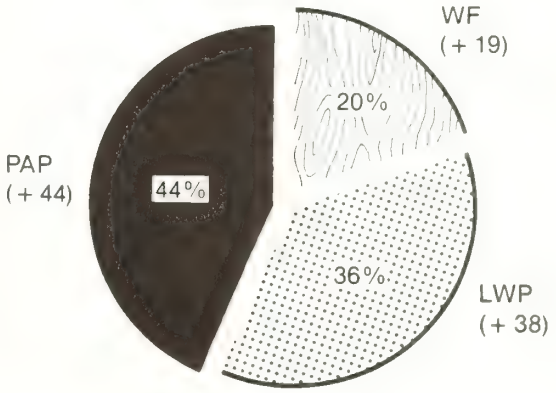


THE SOUTH

1980 Employment—620,567

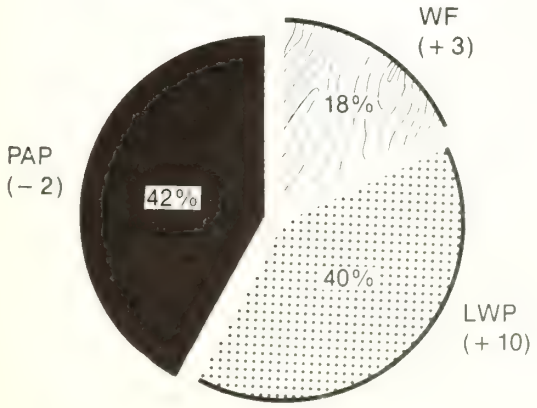


1980 Earnings—$7.96 billion

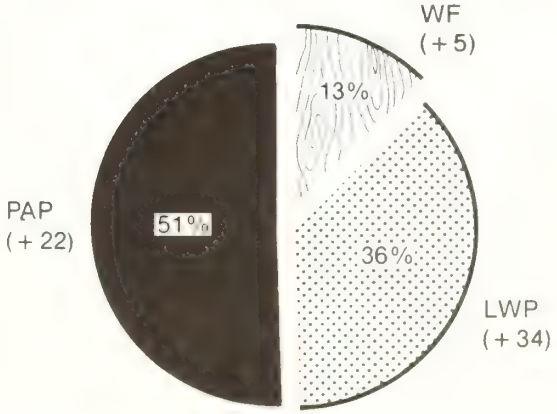


UNITED STATES

1980 Employment—1,634,000



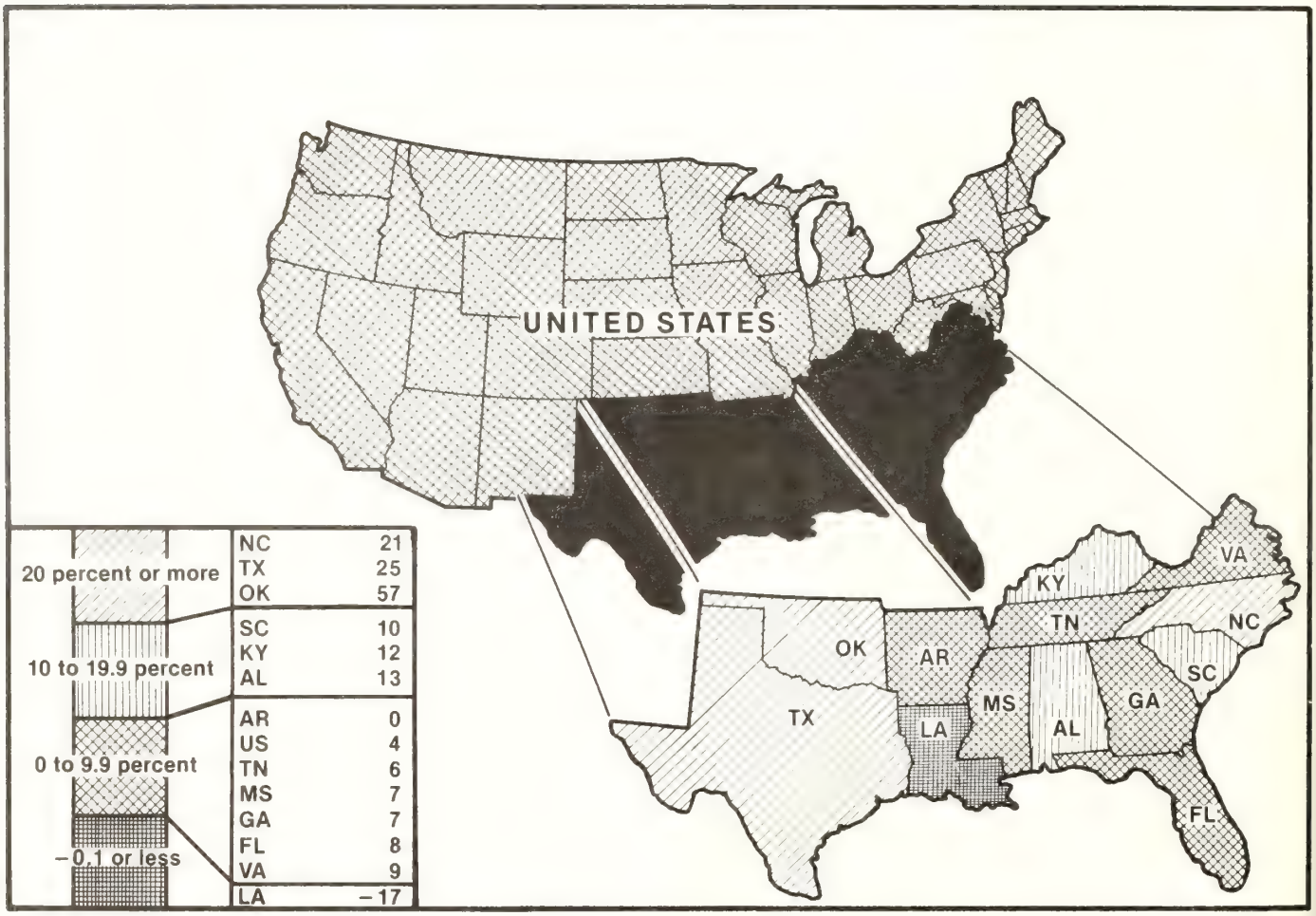
1980 Earnings—$23.65 billion



Numbers in parentheses show percent of change from 1970 to 1980.

Growth of Employment

With the exception of Arkansas and Louisiana, forest products industry employment in each of the Southern States grew faster than did the U.S. counterpart. Employment in two states--Oklahoma and Texas--grew faster than the "all-industry" average of 22.3 percent. Employment growth in Georgia's forest products industry was nearly twice the national rate, and ranked ninth among the 13 Southern States.

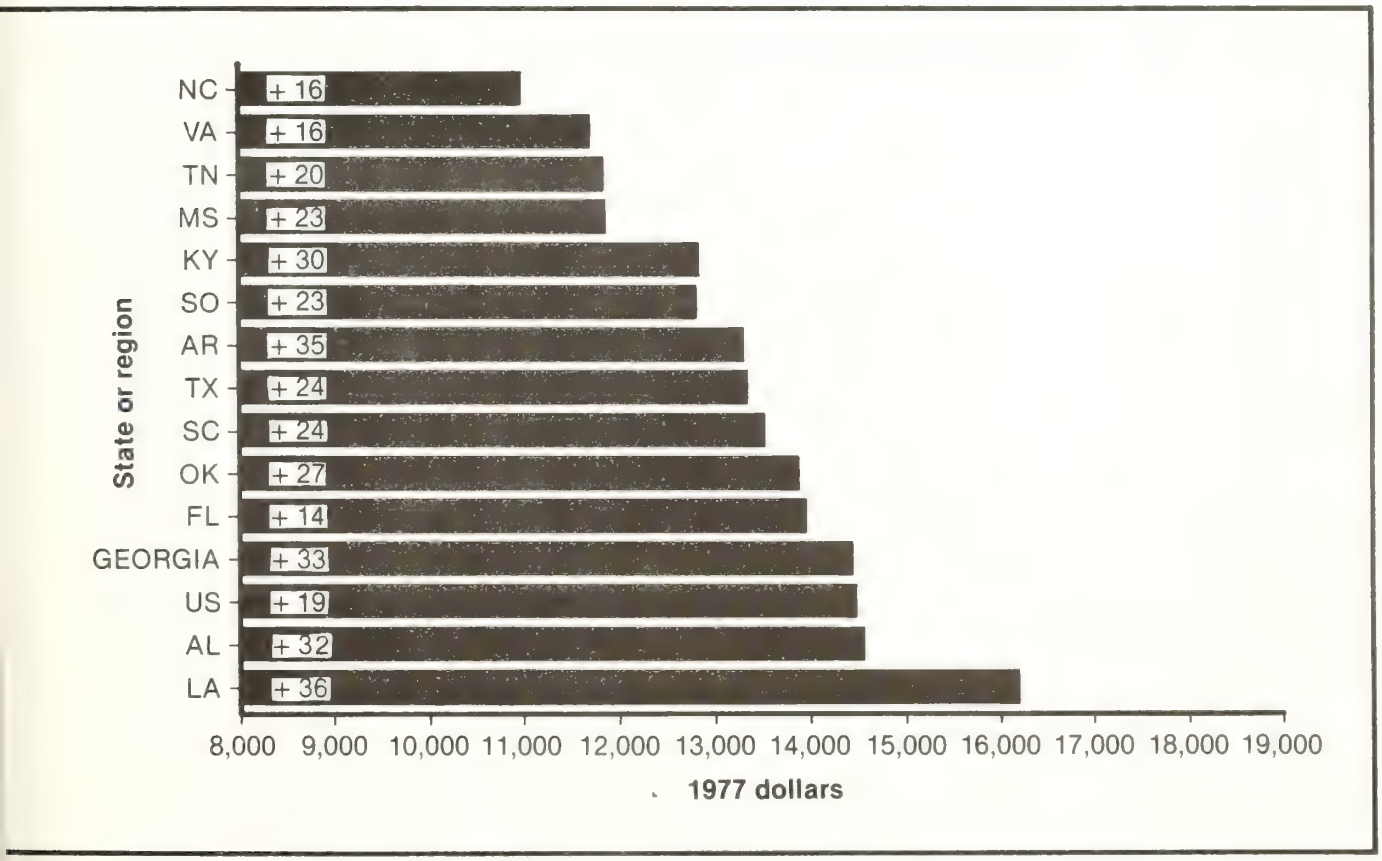


Average Annual Earnings

Average annual earnings per worker in the forest products industry differed significantly by State in 1980: Approximately $5,000 separated the State with the highest earnings--Louisiana--from the State with the lowest--North Carolina. Pulp and allied products manufacturing, which has traditionally paid higher wages than have other forest products industries, dominated Louisiana's forest products industry. Wood furniture, which has paid lower average wages, dominated North Carolina's industry.

Average annual earnings per worker in Georgia's forest products industry matched the industry's U.S. average. In both average annual earnings per worker and growth in earnings, Georgia ranked third in the South.

Generally speaking, paper and allied products dominated the forest products industry in the states with the highest average annual earnings. This relationship reflects higher job skills and unions in the paper industry.



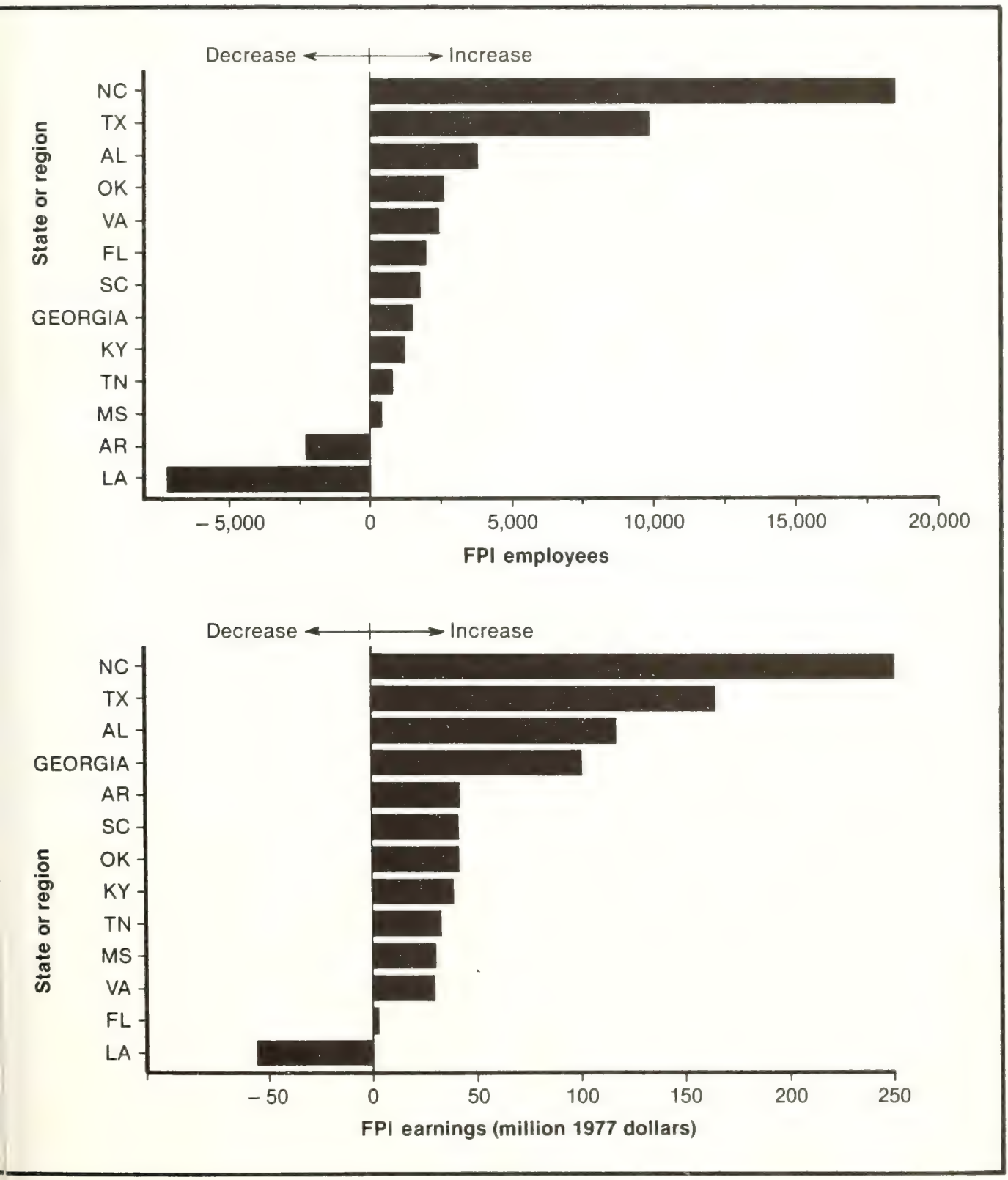
lumbers in bars show percent of change from 1970
) 1980.

Shift in Employment and Earnings

The regional shift shows how much more or less employment and earnings a State would have had in the forest products industry in 1980 than in 1970 had the industry grown at the national rate. For example, Georgia had approximately 1,400 more employees in 1980 than it would have had if its forest products industry had grown at the national rate.

Between 1970 and 1980, in both employment and earnings, the forest products industry increased in every Southern State except Louisiana. Moreover, all but two States increased their share of the Nation's forest products industry employment, and all but Louisiana increased their share of earnings. Increased shares of employment and earnings reflect the comparative advantage the South's forest products industry enjoyed over this industry in the rest of the Nation.

Several factors (for example, relatively lower labor costs, lower raw materials costs, and closer proximity to markets) might account for a region's comparative advantage, although adverse trends with respect to one factor need not reduce a region's advantage. In the case of the South, for instance, increasing labor costs need not adversely affect it's comparative advantage if increased capital or labor productivity offsets higher labor costs.


Decrease
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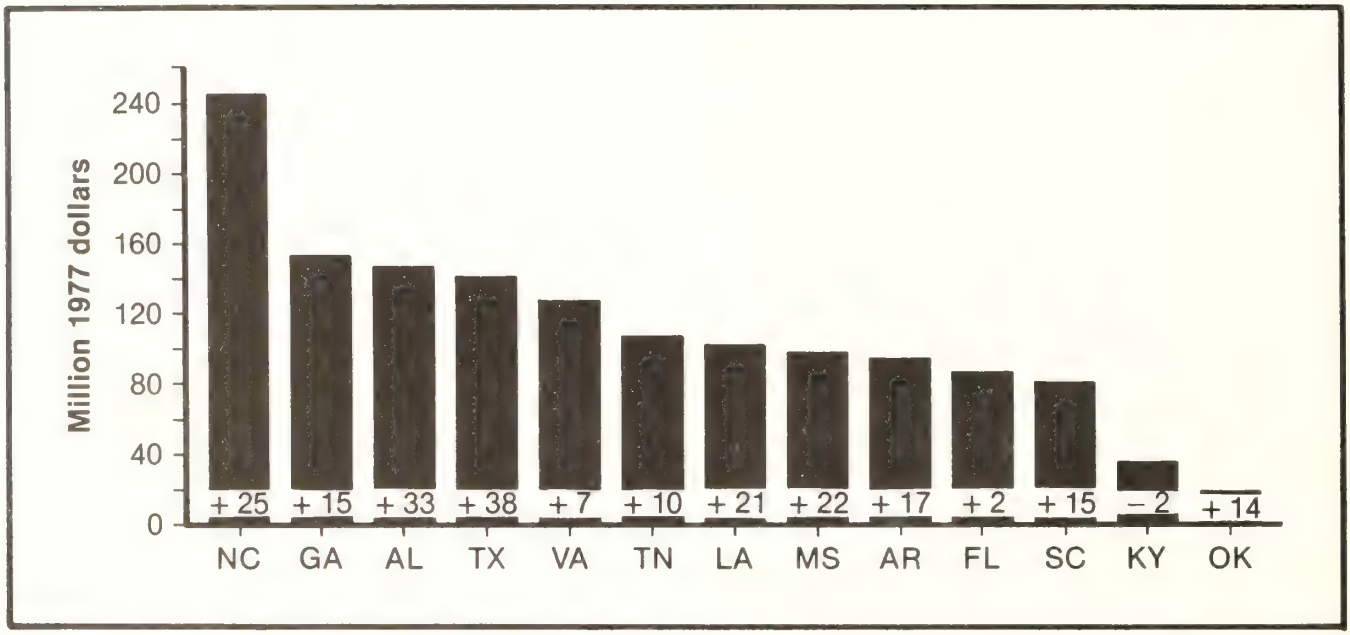
150
200
250
FPI earnings (million 1977 dollars)

Value Added by the Forest Products Industry

In 1977, the forest products industry of North Carolina produced more value added than any other State in the South. Georgia was second among the 13 Southern States, followed by Alabama. Texas was not only one of the leading States in terms of total value added, it also led the South in terms of the change in value added between 1972 and 1977. One State, Kentucky, produced less value added in 1977 than in 1972.

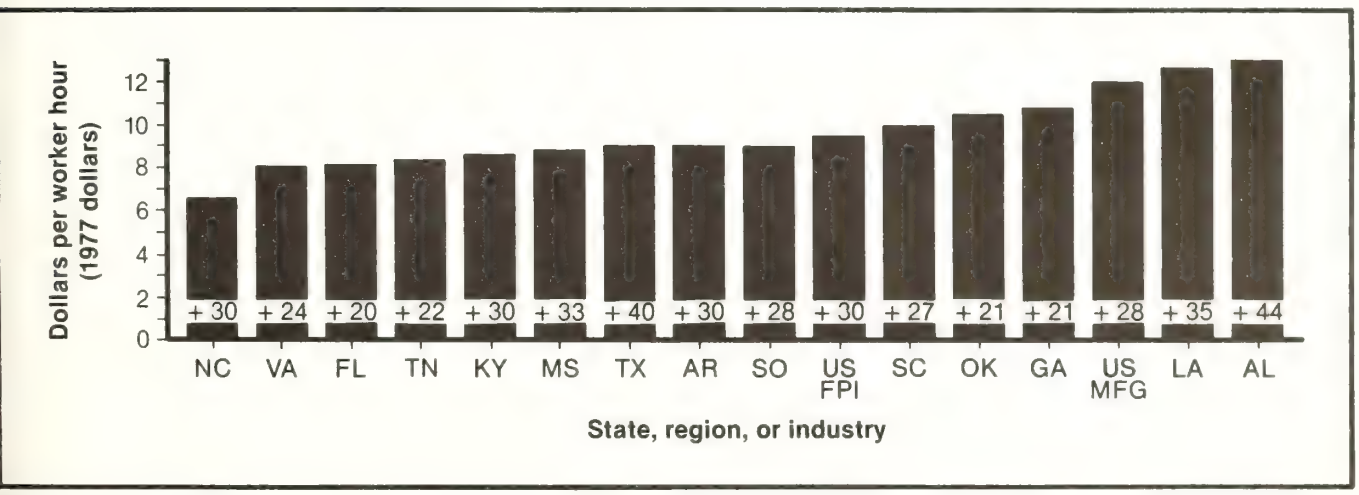


Numbers in bars show percent of changes from 1972 to 1977.

Capital Productivity

The paper and allied products industry, which is more capital-intensive and, therefore, more susceptible to technological change than other forest products industries, exhibited the highest productivity within the forest products industry. The wood furniture industry, on the other hand, is the most labor-intensive of the three industry groups. North Carolina, for example, produced more value added than any other State in the South, but the productivity of its forest products industry in 1977 was the lowest. This reflects the dominant role of the labor-intensive wood furniture industry in North Carolina.

Increases in productivity exceeded increases in payroll per worker between 1972 and 1977 for all the Southern States. This relationship is in part responsible for the South's comparative advantage in the forest products industry. The average productivity for all-manufacturing industries exceeded that of the forest products industries in 11 of the 13 Southern States. But the forest products industries in five Southern States, including Georgia, exceeded the average productivity for the Nation. Furthermore, the increase in productivity of the forest products industry in all but six States exceeded that for all-manufacturing.



Numbers in bars show percent of change from 1972 to 1977.

Acknowledgment

Many helpful suggestions of several reviewers were incorporated in this research paper. This project was partially funded by the USDA Forest Service, State and Private Forestry, Area Planning and Development, State Planning for Forest Resources.

Appendix 1
Tables

Table 1--Total labor and proprietorial employment and income, by industry, Georgia, 1980 [1/]

Industry number	Industry	Employees	Total income
		Number	*Million 1977 dollars* [2/]
Wage and Salary			
1	Agriculture	37,244	504.5
2	Agricultural services, forestry, and fisheries	10,675	102.2
3	Coal mining	25	1.1
4	Oil and gas extraction	69	2.8
5	Metal mining	111	.5
6	Nonmetallic minerals	7,613	110.0
7	Construction	105,270	1,421.7
8	Food and kindred products	59,096	725.6
9	Tobacco	1,347	27.9
10	Textile mill production	117,698	1,205.8
11	Apparel and other textiles	72,517	508.8
12	Paper and allied products	28,428	507.0
13	Printing and publishing	23,445	277.8
14	Chemical and allied products	16,904	271.1
15	Petroleum refining	1,292	25.3
16	Rubber and miscellaneous plastics	14,687	179.0
17	Leather and leather products	2,392	17.2
18	Lumber and wood products, except mobile homes	25,543	297.3
19	Mobile homes	3,606	42.0
20	Wood furniture	5,191	49.8
21	Other furniture and fixtures	4,494	43.2
22	Stone, clay, and glass products	18,031	246.0
23	Primary metals	16,241	267.8
24	Fabricated metals	21,132	277.8
25	Machinery, excluding electrical	21,945	296.7
26	Electrical machinery	20,130	275.3
27	Transportation equipment except motor vehicles	18,091	373.0
28	Motor vehicles	16,165	343.8
29	Ordnance	[3/]--	[3/]--
30	Instruments and related equipment	4,798	56.8
31	Miscellaneous manufacturing	7,105	70.8
32	Railroad transportation	14,313	280.8
33	Trucking and warehousing	35,119	550.0
34	Local transit	2,329	26.3

See footnotes at end of table.

Table 1--Total labor and proprietorial employment and income, by industry, Georgia, 1980[1/](continued)

Industry number	Industry	Employees	Total income
		Number	*Million 1977 dollars[2/]*
Wage and Salary			
35	Air transportation	26,245	636.3
36	Pipeline transportation	474	11.0
37	Transportation services	3,394	46.4
38	Water transportation	3,751	39.0
39	Communications	35,957	702.7
40	Electrical, gas, and sanitation services	20,336	400.9
41	Wholesale trade	158,520	2,543.6
42	Retail trade	343,393	2,729.1
43	Banking	30,522	340.0
44	Other credit agencies	30,890	324.6
45	Insurance	40,314	617.2
46	Real estate and combinations	22,714	291.4
47	Hotel and other lodging	28,571	198.7
48	Personal, miscellaneous business, and repair services	94,929	955.0
49	Auto repair service	14,980	183.6
50	Amusement	11,455	81.0
51	Motion pictures	3,266	22.0
52	Private households	78,003	197.2
53	Medical and other health	75,718	1,145.2
54	Private education	25,844	205.3
55	Nonprofit organizations	52,847	362.2
56	Miscellaneous services	28,574	653.8
57	Federal civilian	84,411	1,272.2
58	Federal military	89,679	726.5
59	State and local government	347,430	3,057.4
Proprietorial			
60	Farm proprietors	73,538	337.1
61	Nonfarm proprietors	155,613	1,710.7
	Total	2,604,414	29,175.8

1/ Source of data for this table for Georgia, other States of the South, and the United States: unpublished data, U.S. Department of Commerce, Regional Economics Measurements Division, Regional Economic Information System (REIS), Washington, DC, 1982. Unpublished data used by the U.S. Department of Commerce in preparing their *County Business Patterns* (CBP) series on employment and payroll were used to differentiate wood-related from nonwood-related employment and earnings. For example, CBP data were used to separate mobile homes (no. 19, above) from the lumber and wood products industry (no. 18). Wood furniture (no. 20) was similarly separated from other furniture and fixtures (no. 21).

2/ The Personal Consumption Expenditures (CPE) deflator, 1977 = 100, was used to deflate actual dollars.

3/ Included with fabricated metals and other related industries.

Table 2--Dependency indexes for Georgia, 1980

(In percent)

Industry	Employment		Georgia excess employment[1/]	Dependency index[2/]
	Georgia	United States		
Agriculture	1.709	1.461	0.248	1.737
Agricultural services, forestry, and fisheries	.490	.618	--	--
Farm proprietors	3.375	3.030	.345	2.414
Coal mining	.001	.274	--	--
Oil and gas extraction	.003	.605	--	--
Metal mining	.005	.109	--	--
Nonmetallic minerals	.349	.137	.213	1.490
Construction	4.831	4.744	.087	.611
Food and kindred products	2.712	1.869	.843	5.907
Tobacco	.062	.074	--	--
Textile mill production	5.402	.931	4.471	31.320
Apparel and other textiles	3.328	1.387	1.941	13.600
Paper and allied products	1.305	.756	.549	3.846
Printing and publishing	1.076	1.374	--	--
Chemical and allied products	.776	1.218	--	--
Petroleum refining	.059	.220	--	--
Rubber and miscellaneous plastics	.674	.796	--	--
Leather and leather products	.110	.259	--	--
Lumber and wood products, except mobile homes	1.172	.709	.463	3.245
Mobile homes	.165	.051	.115	.802
Wood furniture	.238	.323	--	--
Other furniture and fixtures	.206	.188	.018	.127
Stone, clay, and glass products	.827	.731	.097	.679
Primary metals	.745	1.262	--	--
Fabricated metals	.970	1.774	--	--
Machinery, excluding electrical	1.007	2.732	--	--
Electrical machinery	.924	2.313	--	--
Transportation equipment except motor vehicles	.830	1.213	--	--
Motor vehicles	.742	.872	--	--
Instruments and related equipment	.220	.773	--	--
Miscellaneous manufacturing	.326	.466	--	--
Railroad transportation	.657	.584	.073	.511
Trucking and warehousing	1.612	1.401	.211	1.477
Local transit	.107	.294	--	--
Air transportation	1.204	.499	.706	4.944
Pipeline transportation	.022	.023	--	--
Transportation services	.156	.223	--	--
Water transportation	.172	.230	--	--
Communications	1.650	1.482	.168	1.180

See footnotes at end of table.

Table 2--Dependency indexes for Georgia, 1980 (continued)

(In percent)

Industry	Employment		Georgia excess employment[1/]	Dependency index[2/]
	Georgia	United States		
Electrical, gas, and sanitation services	.933	.903	.030	.210
Wholesale trade	7.275	5.786	1.489	10.430
Retail trade	15.759	16.501	--	--
Banking	1.401	1.725	--	--
Other credit agencies	.959	.991	--	--
Insurance	1.850	1.886	--	--
Real estate and combinations	1.042	1.160	--	--
Hotel and other lodging	1.311	1.200	.112	.781
Personal, miscellaneous business, and repair services	4.357	4.694	--	--
Auto repair service	.687	.630	.058	.403
Amusement	.526	.842	--	--
Motion pictures	.150	.243	--	--
Medical and other health	3.475	5.713	--	--
Private education	1.186	1.465	--	--
Nonprofit organizations	2.425	3.012	--	--
Miscellaneous services	1.311	1.635	--	--
Federal civilian	3.874	3.270	.604	4.232
Federal military	4.116	2.680	1.435	10.055
Nonfarm proprietors	7.142	7.663	--	--
Total[3/]	100.00	100.00	14.275	100.00

[1/] U.S. employment minus Georgia employment. Figures may not be exactly equal to Georgia minus U.S. because of rounding. Dashes signify no excess employment.

[2/] Individual industry excess employment expressed as a percent of Georgia's total excess employment (sum of column 4).

[3/] Sum of parts may not equal totals because of rounding.

Table 3--Value added, hours worked, payroll, and capital productivity,[1/] Georgia forest products industry, 1977[2/]

Industry	Value added	Payroll	Hours worked	Productivity	Productivity change, 1972-77
	-- *$ Million* --		*Million*	*$VAMP per hour*	*Percent*
Lumber and wood products	4,924	1,916	357	8.42	42.60
Wood furniture	760	377	79	4.85	3.34
Paper and allied products	9,504	3,785	410	13.95	9.41

[1/] Productivity equals value added (VAMP), minus payroll, divided by hours worked.

[2/] Source: U.S. Bureau of the Census, Census of Manufacturing, for 1972 and 1977, Georgia and the United States, available in 1976 and 1980, respectively. In the few instances where data were not available for some subindustry sectors, the distribution of the number of establishments was used to estimate nondisclosures.

Appendix 2
Georgia Counties by Substate Planning and Development Districts

District code	Counties
a	Cherokee, Fannin, Gilmer, Murray, Pickens, Whitfield
b	Bartow, Catoosa, Chattooga, Dade, Floyd, Gordon, Haralson, Paulding, Polk, Walker
c	Banks, Dawson, Forsyth, Franklin, Habersham, Hall, Hart, Lumpkin, Rabun, Stephens, Towns, Union, White
d	Clayton, Cobb, DeKalb, Douglas, Fulton, Gwinnett, Rockdale
e	Barrow, Clarke, Elbert, Greene, Jackson, Madison, Morgan, Oconee, Oglethorpe, Walton
f	Carroll, Coweta, Heard, Meriwether, Troup
g	Butts, Fayette, Henry, Lamar, Newton, Pike, Spalding, Upson,
h	Baldwin, Hancock, Jasper, Johnson, Putnam, Washington, Wilkinson
i	Chattahoochee, Clay, Harris, Muscogee, Quitman, Randolph, Stewart, Talbot
j	Bibb, Crawford, Houston, Jones, Monroe, Peach, Twiggs
k	Burke, Columbia, Emanuel, Glascock, Jefferson, Jenkins, Lincoln, McDuffie, Richmond, Screven, Taliaferro, Warren, Wilkes
l	Crisp, Dooly, Macon, Marion, Schley, Sumter, Taylor, Webster
m	Bleckley, Dodge, Laurens, Montgomery, Pulaski, Telfair, Treutlen, Wheeler, Wilcox
n	Appling, Bullock, Candler, Evans, Jeff Davis, Tattnall, Toombs, Wayne
o	Baker, Calhoun, Colquitt, Decatur, Dougherty, Early, Grady, Lee, Miller, Mitchell, Seminole, Terrell, Thomas, Worth
p	Ben Hill, Berrien, Brooks, Cook, Echols, Irwin, Lanier, Lowndes, Tift, Turner
q	Bryan, Camden, Chatham, Effingham, Glynn, Liberty, Long, McIntosh
r	Atkinson, Bacon, Brantley, Charlton, Clinch, Coffee, Pierce, Ware

Maki, Wilbur R.; Schallau, Con H; Foster, Bennett B.; Redmond, Clair H. Georgia's forest products industry: performance and contribution to the state's economy, 1970 to 1980. Res. Pap. PNW-332. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 22 p.

Employment and earnings in Georgia's forest products industry, like those of most Southern States, grew significantly between 1970 and 1980. The forest products industry accounted for nearly the same share of the State's economic base in 1980 as in 1970. Moreover, during this period, the State increased its share of the Nation's forest products industry employment and earnings. Pulp and allied products had the highest productivity, but lumber and wood products experienced the largest increase in productivity between 1972 and 1977.

Keywords: Forest products industries, economics in wood industry, Georgia.

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Lumber Recovery From Ponderosa Pine in Northern California

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Abstract

Ernst, Susan; Pong, W. Y. Lumber recovery from ponderosa pine in northern California. Res. Pap. PNW-333. Portland, OR: U.S. Department of Agriculture, Pacific Northwest Forest and Range Experiment Station; **1985.** 22 p.

Lumber recovery information from 942 logs from old- and young-growth ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) trees in northern California is presented. More than 58 percent of the lumber volume was found in 5/4 Shop, Moulding, and Select grades. About 25 percent of the total lumber volume was Moulding, and 24 percent was Standard and Better Dimension. Lumber volume recovery is presented on the basis of cubic feet and board feet. Volume recovery varied by scaling diameter but not by log grade. Value recovery and percent volume by lumber grade did vary by log grade and diameter, but no difference was found between the grade 1 and the grade 2 logs.

Keywords: Lumber yield, lumber recovery, ponderosa pine, *Pinus ponderosa,* California (northern), northern California.

Research Summary

Lumber recovery information for 942 logs from old- and young-growth ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) trees in northern California is presented. Over 58 percent of the lumber is 5/4 Shop, Moulding, and Select grades. Nearly 25 percent of the total lumber volume was Moulding; 24 percent was Standard and Better Dimension.

Information is presented on the basis of cubic feet and board feet. Lumber volume recovery varies by scaling diameter but not by log grade. Cubic recovery percent is estimated for all the logs combined, and overrun is estimated separately for old- and young-growth logs. The overrun for old-growth logs smaller than 17 inches is slightly higher than the overrun for the young-growth logs because of the effects of taper and log length.

Lumber grade recovery varies by scaling diameter and log grade except for grade 1 and grade 2 logs. The percentage of higher grade lumber increased as diameter and quality of logs increased. The value recovery coincides with the lumber grade recovery. Lumber values were indexed to Western Wood Products Association quarterly prices to allow easier updating to current prices. An additional method is also presented that allows the direct estimate of lumber volume and value from the cubic volume of logs.

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Introduction

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is a major softwood species in the Western United States. In California, it makes up more than 19 percent of the commercial softwood timber volume (USDA Forest Service 1974). Since the last product recovery study was conducted on this species some 20 years ago, timber size, product mix, and product sizes have changed. Currently, more Dimension grades of lumber are being produced from ponderosa pine, and there has been a marked increase in the utilization of young growth. Because of these changes, a need has developed for up-to-date information on volume and grade recovery of lumber from ponderosa pine. Land owners and mill managers depend on current product recovery information to make decisions on timber appraisals and log allocation, and to insure efficient utilization. Information in this report is from a product recovery study conducted in 1978 in cooperation with Region 5 (Pacific Southwest Region) of the USDA Forest Service.

The objectives of this paper are to provide information on lumber volume recovery, lumber grade distribution, and value of logs from young- and old-growth ponderosa pine trees in northern California. Specific objectives are to develop equations for predicting lumber volume, grade, and value yields, and to use these equations to test for differences between log grades.

Methods

Sample Selection

The study sample consisted of 150 old-growth and 60 young-growth trees selected from areas in the Sierra Nevada in the Plumas and Tahoe National Forests in California (fig. 1). Old-growth trees were selected from eight areas that covered the range of Dunning's Site Classes (Dunning 1942). Young-growth trees (less than 100 years old) were selected from two areas: a site 1 and a site 2 stand, both previously thinned. Both old- and young-growth samples were stratified by size (diameter at breast height—d.b.h.) and quality (grade of the butt log) (Gaines 1962). The sample trees ranged from 8 to 56 inches in d.b.h. for the old growth and from 8 to 32 inches for the young growth. The sample was selected by 2-inch diameter classes and averaged six trees per class. The sample was selected to cover the entire range of tree diameters and quality. The logs from these trees will not approximate the normal production run of diameters and grades, but they will provide recovery information that can be used for estimating recovery for any set of diameters and grades. Trees were felled and bucked according to normal industry practices in the area, except that the minimum log size included in this study was 6 inches in diameter inside bark at the small end and 8 feet in length.

Log Grading and Scaling

Field length logs were rolled out in the mill yard and scaled by both USDA Forest Service and industry scalers. Scribner segment scale with a 20-foot maximum length was taken (USDA Forest Service 1973). Gross cubic scale measurements were taken to one-tenth inch for diameter and to one-tenth foot for length. Bruce's (1982) butt log formula was applied to the butt logs, and Smalian's formula was applied to the upper logs to calculate the gross cubic scale volumes. Net cubic volume was determined by reducing the gross volume for voids, soft rots, and charred wood. Gaines' (1962) grading system was used for grading logs; grades 1, 2, 3, and 5 were used for the old-growth logs and grades 4 and 5 for the young-growth logs. Logs were rescaled after they were debarked and bucked into short logs on the mill deck. Information in this report is based on the Scribner scale taken on the mill deck and the cubic scale (with a 20-foot maximum length) taken in the mill yard.

Processing

The number of logs processed is shown in table 1. Production equipment in the sawmill includes: one single cut headsaw, one debarker, one single band vertical resaw, one single band horizontal resaw, two edgers, one gang bull edger, and one trim saw. Sawmill production averages about 150,000 board feet of lumber per shift.

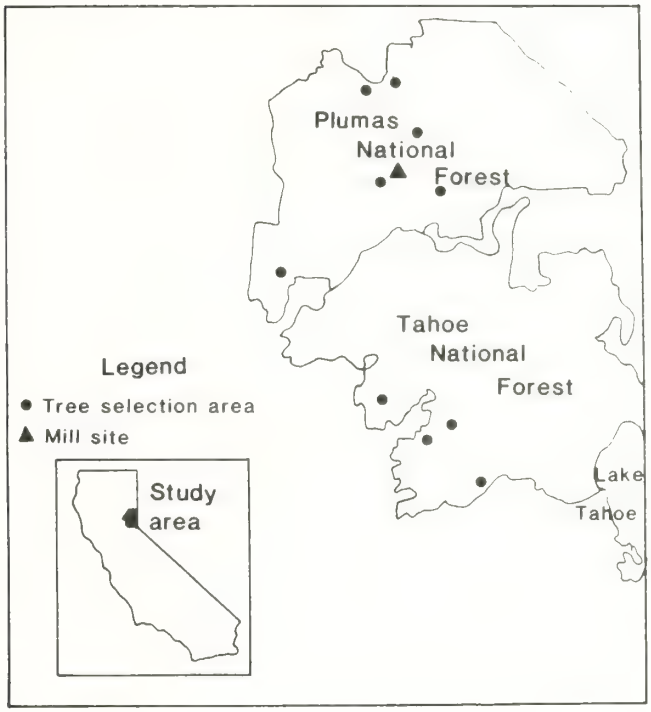

Figure 1.—Approximate location of study areas in the central Sierra Nevada.

Table 1—Number of logs by diameter and grade

Diameter class	Grade 1	2	3	5	Young growth
Inches			Number		
6-7				35	51
8-9				35	45
10-11			1	48	58
12-13			3	45	47
14-15			5	35	37
16-17		3	7	28	21
18-19	1	4	4	26	22
20-21	3	2	9	20	15
22-23	5	7	9	22	4
24-25	4	11	5	12	3
26-27	5	5	6	17	
28-29	5	7	6	13	
30-31	5	5	5	12	
32-33	5	3	10	10	
34-35	5	4	3	11	
36-37	8	5	7	2	
38-39	3	7	3	4	
40-41	9	5	4	4	
42-43	8	2	4	2	
44-45	5	4	5		
46-47	4	2		2	
48-49	4	1		1	
50-51	3				
Total	82	77	96	384	303

A system of paint colors and numbers was used in the mill to identify each board so that it could be identified by the log and tree from which it was cut. The lumber was kiln dried and then was graded under the supervision of a Western Wood Products Association (WWPA) inspector according to WWPA grading rules (Western Wood Products Association 1977). Each log was sawn to recover the maximum value. The following lumber grades were produced during the study: Select, Moulding, Shop, Dimension, and Common. Lumber was not all in the same condition when it was graded; Moulding and Select were rough, Shop was surfaced two sides, and Dimension and Common were surfaced four sides. A tally of length, width, thickness, and grade of each board was made. The lumber items were separated into 16 grades of lumber during the study. In this paper we have combined these grades into five grade groups:

Grade group	Lumber grades	Percent of lumber volume
Moulding and Better (Mldg & Btr)	B and Better Select	1.8
	C Select	2.6
	D Select	4.2
	Moulding	25.3
2 Shop	Factory Selects	.5
	1 Shop	4.5
	2 Shop	14.8
3 Shop	3 Shop	8.3
	Shop Out	1.6
Standard and Better (Std & Btr)	No. 2 and Better or Standard and Better	24.0
	3 and Better Common	.2
Utility and Economy (Util & Econ)	No. 3 or Utility	9.2
	Economy	2.5
	4 Common	.3
	5 Common	.1

Analysis

The objective of the analysis was to develop equations for predicting volume, grade, and value yields of lumber from logs from old- and young-growth trees.

Volume

Two approaches were used to analyze the volume of lumber recovered for the range of log scaling diameters (D): cubic recovery percent (CR%) and overrun (OR) (Fahey and Woodfin 1976). Cubic recovery percent is the ratio of cubic feet of lumber produced from a net cubic foot (CF) of log volume. Overrun is the percent of board-foot (BF) volume of lumber produced that is more than the net board-foot scale of that log. Cubic recovery percent and overrun vary by diameter, and generally a curvilinear function with diameter is used.

Cubic recovery percent.—Because both the lumber volume and the log volume are measured in cubic feet, cubic recovery percent gives the most accurate representation of the lumber volume to log volume relationships (Fahey and Snellgrove 1982). Cubic recovery percent, therefore, was used to test the hypothesis that lumber volume recovery does not vary by log grade. Several curve forms using diameter and transformations of diameter (1/D, $1/D^2$) as independent variables were tried (singly or in combination) to find the regression equation that best fit each log grade. The selection of the final curve forms was based primarily on the regression model having the highest coefficient of determination (R^2) and/or the lowest mean square error (MSE). Covariance analysis was used to compare the four grades of old growth, the two grades and sites of young growth, and the old- and young-growth logs. All testing was done at the 0.05 level of significance. The initial analysis was done on rough green lumber, but regressions were also developed for cubic recovery of surfaced dry lumber and of rough green lumber and sawdust combined. Sawdust volume is found by multiplying one-half the saw kerf by the surface area of the board.

Overrun.—Overrun curves were fitted separately to old-growth and young-growth logs; model forms used were the same as for cubic recovery. Coefficient of determination and mean square residual statistics were again used in choosing the best fitting equation. Covariance analysis was used to test for differences between the equations for old- and young-growth logs.

Board feet per cubic foot of lumber.—Another ratio related to volume is board feet per cubic foot of lumber (BF/CF) (Fahey and Woodfin 1976). This is defined as the ratio of the board feet of lumber, measured in nominal dimensions, to cubic feet of rough green lumber, measured in actual dimensions. This ratio is used to convert cubic volume of lumber, predicted from CR%, to board feet or marketing units. This ratio also varies by diameter, and various transformations of D were tested as independent variables. Board feet per cubic foot was regressed against diameter for old- and young-growth logs, and comparisons were made to test for differences between them.

Grade

Regression lines were fitted to cumulative percent volume by lumber grade groups (Util & Econ, Util & Econ and Std & Btr., and so forth) for each log grade. Again, D, 1/D, and $1/D^2$ were tested to find the best fitting regression. Covariance analysis was used to test for differences in percent of the amount of cumulative lumber grades among log grades.

Value

Value is normally expressed as either value per unit of log scale or value per unit of lumber. The total value of each log is found by multiplying the volume of lumber in each grade by its appropriate price. The prices used to calculate the total log value were taken from the WWPA December 1982 quarterly price index list (appendix 1). These log values include only lumber value, not the value of chips, other byproducts, or costs.

In this analysis, our objective is to evaluate the effects of log grade on value to determine if the log grades are effectively separating the resource quality. Average value, dollars per thousand board feet lumber tally ($/MLT), was used to test for differences in log grades. Average value per unit of lumber is the best indicator of differences between log grades because it reflects only the difference in inherent biological qualities (growth patterns, decay) and mismanufacturing and does not include bias caused by scaling.

The independent variables and transformations used for volume recovery were also used in the analysis of value. Model forms chosen were again based on R^2 and MSE statistics. The regression lines were plotted and covariance analysis was used to test for overall differences between log grades. If differences existed, paired comparisons were made between adjacent log grades (grade 1 vs. grade 2, grade 3 vs. grade 5, and so forth).

Direct Product Estimators

The preceding methods are useful for predicting recovery volume and value of logs by diameter, but another method is used to directly predict the volume of lumber and byproducts and the value of the lumber from cubic scale volumes (Fahey and others 1981). Net cubic scale was used as the independent variable; and a linear regression was used to predict lumber volume, chip volume, and lumber value. Regression equations were estimated for predicting volume of both old- and young-growth logs. Comparisons were made to test for differences. For predicting value, separate equations were developed for each grade of old-growth logs and for all young-growth logs combined. These equations were then tested for differences.

Results and Discussion

Volume

Cubic recovery percent.—Cubic recovery percent was found to be independent of log grade for the four old-growth log grades; therefore, all the data for old growth were pooled. A comparison of two sites and two log grades of young-growth logs again showed no statistical difference. A comparison of young-growth versus old-growth logs showed a statistical difference but not a practical difference; therefore, the cubic recovery percent curves are based on the pooled study data. As shown in figure 2, CR% increased sharply from 5 to 15 inches, then leveled off. The low recovery from the smaller diameter logs indicates that mills are relatively inefficient in converting these logs to lumber; therefore, a higher percentage of the log volume ended up as chips or hog fuel. Curves for CR% of surfaced dry lumber and of rough green lumber and sawdust are also shown in figure 2. The percentage of cubic volume of the log that was converted to chips can be found by subtracting the percentage of cubic recovery of rough green lumber and sawdust from 100 percent. Percentage of cubic volume of the log converted to surfaced dry lumber, shrinkage and planer loss, sawdust, and chips by scaling diameter are presented in table 2.

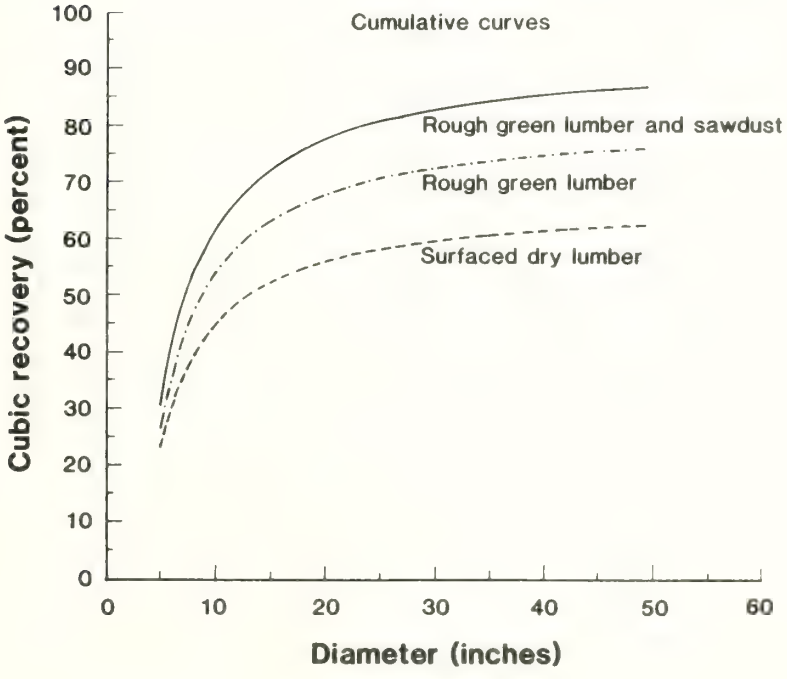

Figure 2.—Relationship of cubic volume recovery to scaling diameter for all logs combined. CR% increases as log size increases to 15 inches in diameter and then remains constant. The figure shows that the mill recovered a higher percentage of lumber volume from larger logs

	R^2	MSE
CR% of surfaced dry lumber = 66.885 − 218.273(1/D)	0.518	0.0077
CR% of rough green lumber = 81.645 − 277.307(1/D)	0.557	0.0107
CR% of rough green lumber and sawdust = 93.279 − 315.355(1/D)	0.554	0.0140

Table 2—Volume recovery information for ponderosa pine in northern California

Log diameter 1/	Cubic recovery percent				Scribner overrun		Board feet per cubic foot	
	Surfaced dry lumber volume	Shrinkage and planer loss	Sawdust	Chips	Old growth	Young growth	Old growth	Young growth
Inches	Percent							
6	30	5	5	60	71	42	14.8	15.0
7	36	6	6	52	81	54	15.1	15.0
8	40	7	7	46	84	59	15.0	14.9
9	43	8	7	42	82	61	14.8	14.8
10	45	9	8	38	79	61	14.6	14.6
11	47	9	8	36	75	61	14.3	14.5
12	49	10	8	33	71	59	14.1	14.3
13	50	10	9	31	66	58	13.9	14.2
14	51	10	9	30	62	56	13.6	14.1
15	52	11	9	28	58	55	13.4	14.0
16	53	11	9	27	55	53	13.3	13.9
17	54	11	9	26	51	51	13.1	13.8
18	55	12	10	23	48	50	12.9	13.7
19	55	12	10	23	45	48	12.8	13.6
20	56	12	10	22	42	47	12.6	13.6
21	56	12	10	22	39	46	12.5	13.5
22	57	12	10	21	37	45	12.4	13.4
23	57	12	10	21	34		12.3	
24	58	12	10	20	32		12.2	
25	58	12	10	20	30		12.1	
26-29	59	13	10	19	26		12.9	
30-33	60	13	10	17	19		11.6	
34-37	61	13	11	16	14		11.3	
38-41	61	13	11	15	10		11.1	
42-45	62	13	11	14	7		10.9	
46-49	62	14	11	13	4		10.8	

1/ 4-inch diameter classes were used for diameters larger than 25 inches because predicted values change very little in this region of the curve.

Overrun.—The same model forms chosen for cubic recovery were used to develop separate regression equations for old- and young-growth logs. A comparison of the two equations showed a statistically significant difference (fig. 3). One reason the old-growth logs smaller than 17 inches have higher overruns is the effect of taper. The old-growth logs had a higher taper factor (0.24 inch per linear foot of log) than the young-growth logs (0.14 inch per linear foot of log). The taper is different because the small diameter old-growth logs are from the crown area whereas the young-growth logs of the same size are from the main bole of the tree. The overrun may also be affected by log length; the young-growth logs were bucked primarily into 16-foot lengths, and the small diameter old-growth logs were bucked into lengths ranging from 10 to 18 feet. The overrun for the young-growth sample is slightly higher than the old-growth sample for logs larger than 17 inches because of the change in product mix. Average percentage of overrun by scaling diameter is presented in table 2.

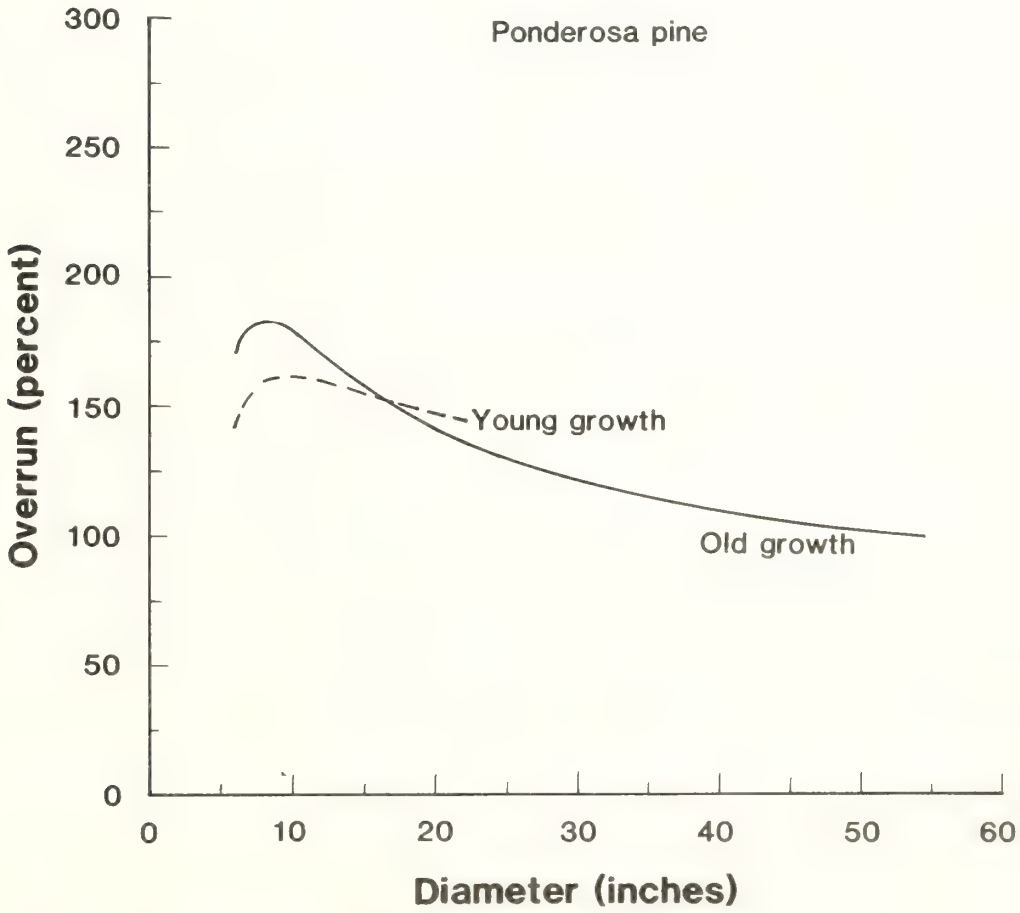

Figure 3.—Scribner overrun decreases as log size increases because of the combined effects of log scale, taper, and product mix. Within the 6- to 16-inch range the overrun for young-growth logs is lower than the overrun for old-growth logs.

		R^2	MSE
Old growth:	$OR = -31.807 + 1846.302(1/D) - 7388.072(1/D^2)$	0.292	1505
Young growth:	$OR = 7.588 + 1039.770(1/D) - 5007.926(1/D^2)$	0.024	1473

Board feet per cubic foot of lumber.—Comparisons of the regression lines for old growth and young growth showed a significant difference, so separate lines are shown in figure 4. The BF/CF ratios for both old growth and young growth are given by diameter class in table 2. This ratio is useful not only in converting from cubic feet to board feet but also in comparing the efficiency of different mills. For example, in this study the 2-inch Dimension and the 6/4 Shop were both sawn to

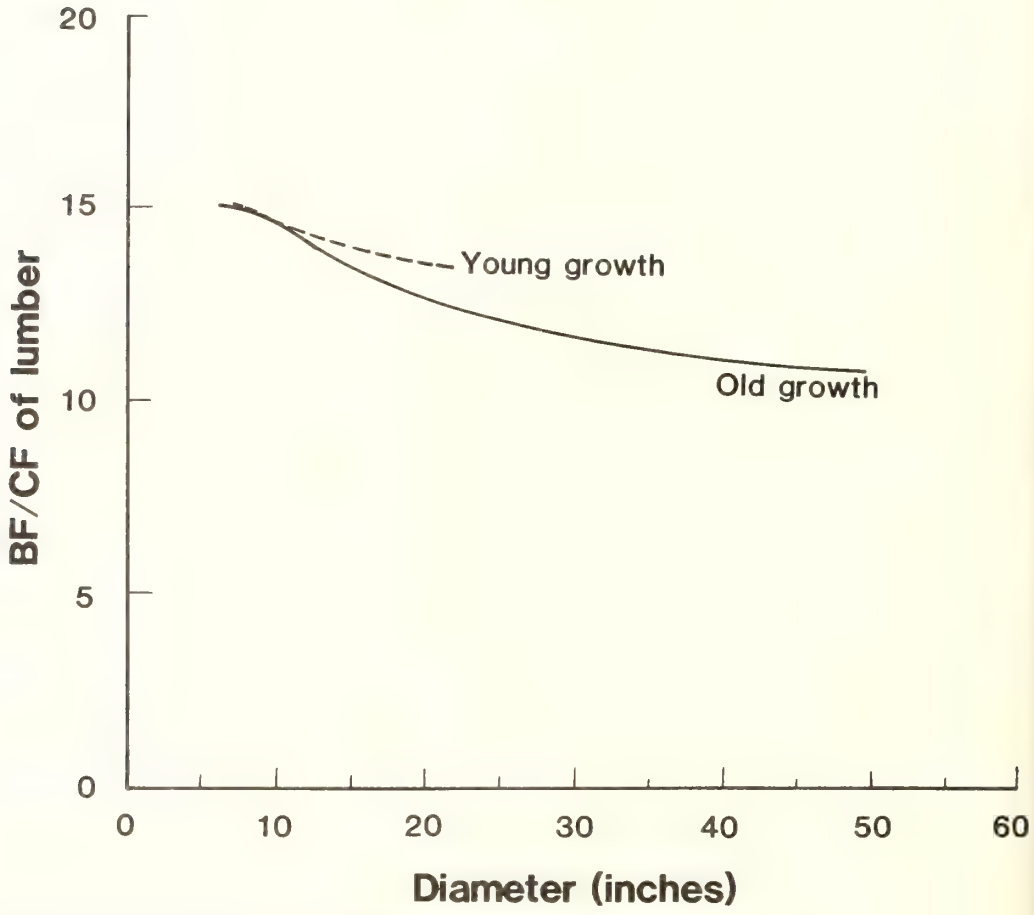

Figure 4.—The BF/CF ratio of lumber decreases as log size increases because of the change in product mix from 2-inch Dimension to 6/4 Shop.

		R^2	MSE
Old growth:	$BF/CF = 9.182 + 83.968(1/D) - 300.22(1/D^2)$	0.860	0.294
Young growth:	$BF/CF = 11.894 + 39.442(1/D) - 123.22(1/D^2)$	0.397	0.378

the same rough green thickness. As a result, both items used the same cubic volume of wood, but they have different board-foot volumes (table 3) because the board-foot volume is calculated with 1½ inches as the nominal thickness of the Shop whereas the Dimension is a full 2 inches. The board-foot volume of the 6/4 Shop will only be three-fourths that of the 2-inch Dimension; therefore, the BF/CF ratio of the Shop will be lower. This is evident in figure 4 where the BF/CF curve decreases with increasing log size because more Shop is manufactured from the larger logs.

Table 3—Comparison of board feet per cubic foot for 2 sizes of lumber products

Nominal inches	Actual inches	BF/CF 1/
6/4 x 12	1.66 x 11.75	11.07
2 x 12	1.66 x 11.75	14.76

1/ $\text{BF/CF} = \frac{144 \times \text{board feet per lineal foot}}{\text{actual thickness} \times \text{actual width}}$.

Lumber recovery factor.—A ratio related to volume that is commonly used in the wood products industry is lumber recovery factor (LRF); LRF is the board-foot volume of lumber produced from a cubic foot of log. It can be estimated by multiplying the CR% by the BF/CF ratio; it varies in the same way the BF/CF ratio does with changes in sizes of rough green products and in product mix.

One problem with both LRF and OR is that they are mill specific. Since both terms use a board-foot measure of lumber volume, they are directly tied to a particular mill's efficiency (Olson 1984). On the other hand, CR% is applicable to most mills; that is, most mills produce the same cubic volume of rough green lumber from logs of equal volume. The major differences in lumber recovery between mills are the changes in rough green "target" sizes of the lumber and the product mix. These differences are not accounted for when board foot is used as the measure of lumber, as in OR and LRF. When cubic feet are used to measure the lumber, the actual fiber used is measured and differences are accounted for. Since cubic feet are not used as a market unit, the BF/CF is an easy way to convert cubic feet to board feet for any mill. The BF/CF can also be used to convert published CR% values to actual production in board feet for a particular mill's rough green target sizes and product mix.

Grade

Regression lines were fitted to the cumulative percentages of lumber grades for each log grade. Because covariance analysis showed that there was little practical difference between the lumber grade percentages for grade 1 and grade 2 logs, recovery data for the two log grades were combined to produce a common set of curves. Separate curves were developed for grade 3, grade 5, and young-growth logs (fig. 5). These curves show that the percentage of higher grade lumber not only increases with higher log grades but also increases as log diameter increases for all log grades. Actual percentage of volume in each lumber grade rather than the cumulative percentage is given in appendix 2.

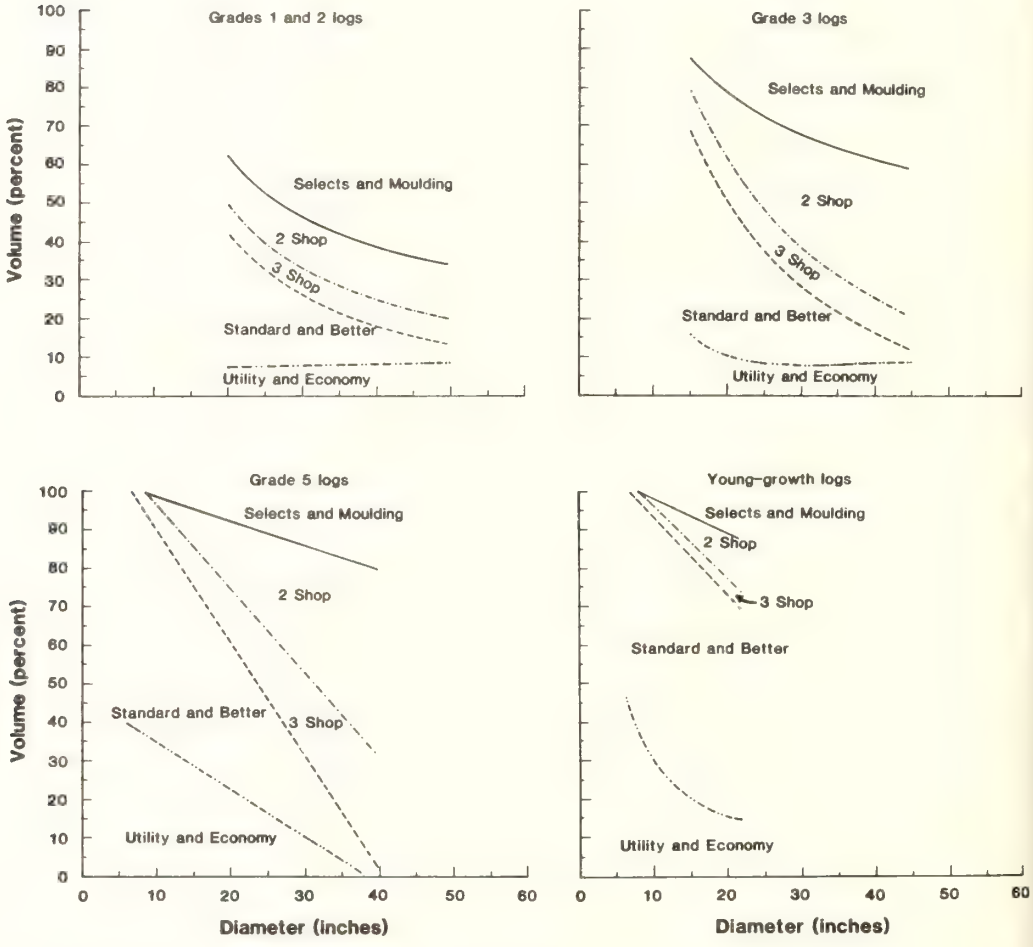

Figure 5.—Percentage of lumber volume by diameter is shown for each log grade. The general trend is that the higher grades of lumber (2 Shop, Moulding) are produced from the higher grade and larger diameter logs.

Value

Average value (dollars per thousand lumber tally—$/MLT) was predicted for each log grade. The regression equations for the grades were compared and no statistical difference was found between grade 1 and grade 2. These results agree with previous results of the volume recovery and percent volume by grade recovery for these two log grades. Grade 1 and 2 logs were again combined to form a single regression line for estimating $/MLT. The grading system separates the value for grade 3 and grade 5 logs (fig. 6). Young-growth logs from 5 to 15 inches in diameter have the same average lumber value as grade 5 logs of the same size. Young-growth logs larger than 15 inches have higher lumber values than the grade 5 logs, probably because most 15- to 22-inch young-growth logs are butt logs whereas the corresponding old-growth grade 5 logs are upper crown logs with many more larger knots.

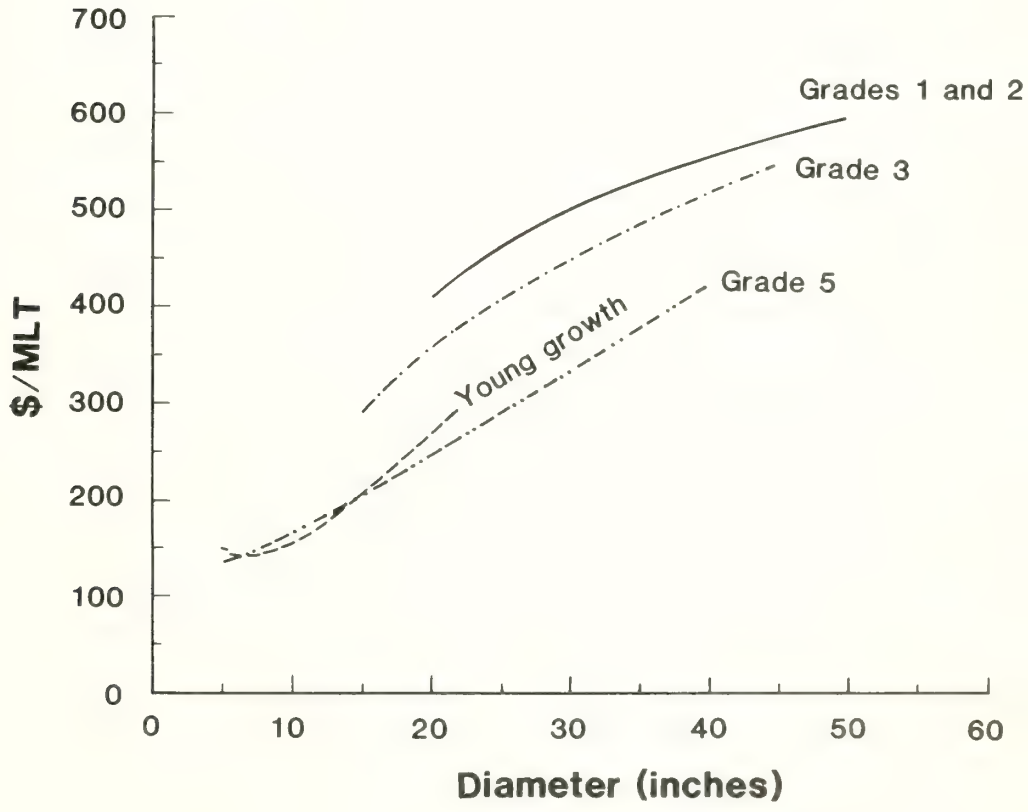

Figure 6.—The log grading system (Gaines 1962) for ponderosa pine effectively separates logs by their value. Although there is no difference between grade 1 and grade 2 logs, grade 3 and grade 5 logs are proportionally lower in value. The young-growth logs have a higher value than grade 5 logs larger than 15 inches because most young-growth logs of that size are butt logs.

		R^2	MSE
Grades 1 and 2:	$/MLT = 593.51 + 1.804(D) − 4382.97(1/D)	0.321	7112
Grade 3:	$/MLT = 391.06 + 4.782(D) − 2587.62(1/D)	0.590	4670
Grade 5:	$/MLT = 59.72 + 8.976(D) + 160.11(1/D)	0.663	2902
Young growth:	$/MLT = -56.04 + 14.62(D)	0.456	2168

Because the average lumber values used to estimate the regressions were based on WWPA quarterly index prices, adjustments to the value can be easily made when prices fluctuate. Values can be updated by multiplying the average value by the proportional change in the index. For example, the index price for coast-inland north ponderosa pine for December 1982 was $309.90, and the quarterly average for April-June 1983 was $394.27; the lumber prices can be updated by multiplying the average log value by $394.27 divided by $309.90.

Direct Product Estimators

Direct product estimators can be a useful tool for land managers or timber buyers. The advantage is that only cubic volume and number of logs are needed for predicting lumber and chip volume and lumber value. Lumber volume in board feet was predicted for old- and young-growth logs (fig. 7). A comparison of the regression lines showed that they were different which coincides with the results of the other recovery predictors for board feet, BF/CF, and OR. The volume of chips in cubic feet is predicted for all logs by use of the equation:

Chip volume (ft^3) = 2.084(number of logs) + 0.1687 (net cubic scale).
r^2 = 0.580; MSE = 63.

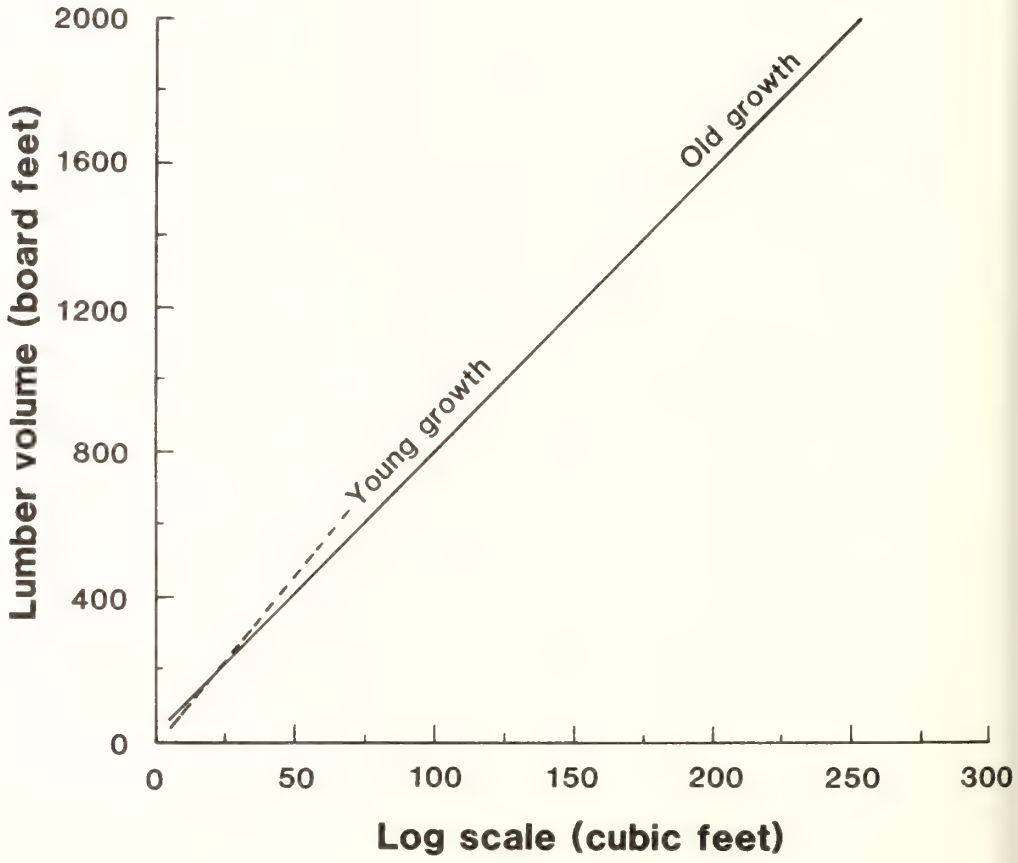

Figure 7.—The volume of lumber in board feet can be estimated from the net cubic scale

Old growth: BF = 18.451(number of logs) + 7.835(net cubic scale).
R^2 = 0.982; MSE = 3630.
Young growth: BF = -10.471(number of logs) + 9.425(net cubic scale).
R^2 = 0.957; MSE = 625.

The lumber value was predicted for each grade of old growth; comparison showed that again no difference could be detected between grade 1 and grade 2 logs, but grade 3, grade 5, and young growth were different (fig. 8).

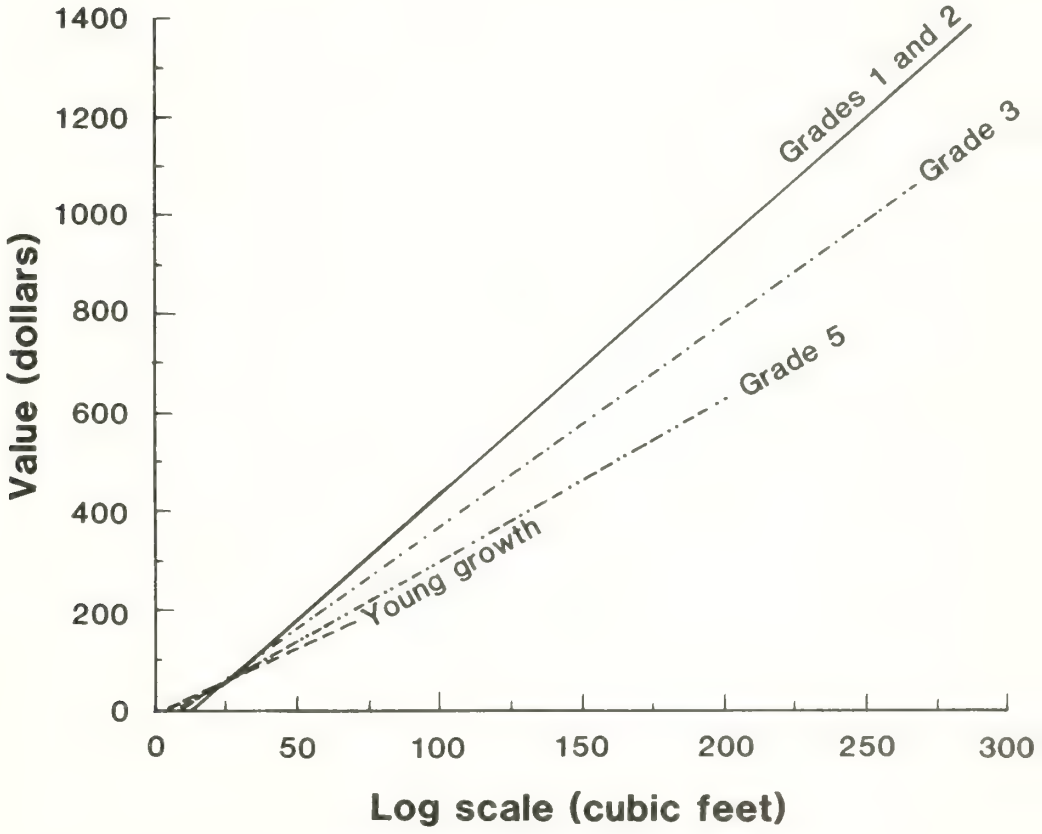

Figure 8.—The dollar value of the lumber from each ponderosa pine log can also be predicted from the net cubic scale for each log grade

Grades 1 and 2: Dollars = -65.259(number of logs) + 5.059(net cubic scale). $R^2 = 0.870$; MSE = 12346.

Grade 3: Dollars = -45.790(number of logs) + 4.144(net cubic scale). $R^2 = 0.948$; MSE = 2566.

Grade 5: Dollars = -28.069(number of logs) + 3.279(net cubic scale). $R^2 = 0.930$; MSE = 986.

Young growth: Dollars = -14.439(number of logs) + 2.793(net cubic scale). $R^2 = 0.873$; MSE = 179.

Application

The information provided in this report can be used to aid mill managers and timber purchasers in decisionmaking. The following examples show two ways of estimating recovery of lumber volume and value. In the first example both the log diameter and either the net Scribner or the net cubic log scale are known, whereas the second example uses only the number of logs and the net cubic scale.

Example 1. Recovery information by diameter.

Sample logs:

			Net scale	
Diameter	Length	Log grade	Scribner	Cubic
(Inches)	(Feet)		(Board feet)	(Cubic feet)
20	16	5	280	43.6
35	16	1	840	113.3

A. Lumber volume can be predicted from either the net Scribner or the net cubic scale by the use of overrun and cubic recovery percent values from table 2.

1. For overrun, add 100 percent to the table 2 value and multiply the answer by the net Scribner scale:

280BF × 142 percent = 398 BF of lumber.
840BF × 114 percent = 958 BF of lumber.

2. For CR%, multiply the table 2 value[1/] by the net cubic volume, then multiply the answer by the BF/CF ratio[2/] for the number of board feet of lumber:

43.6 CF × 68 percent = 29.6 CF of lumber.
29.6 CF × 12.6 BF/CF = 373 BF of lumber.

113.3 CF × 74 percent = 83.8 CF of lumber.
83.8 CF × 11.3 BF/CF = 947 BF of lumber.

A slight difference may occur between the volumes predicted by the net Scribner scale and the net cubic scale because of the variation in each prediction equation.

[1/] The cubic recovery percent should be based on rough green lumber and is equal to the sum of the table 2 values for the percent recovery for surfaced dry lumber and the percent recovery for shrinkage and planer loss.

[2/] The BF/CF ratio may be either the value from table 2 or, if it is known, the value for a specific mill can be used for a more accurate estimate.

B. Once the board-foot volume of lumber has been estimated, the value of the lumber can be predicted two ways; from the average lumber value ($/MLT) or from prices for the individual lumber grades.

1. Using equations for $/MLT from figure 6, solve for the diameter and grade of the log, then multiply the $/MLT by the board feet of lumber:

$$\begin{aligned}\text{Grade 1: } \$/\text{MLT} &= 593.51 + 1.80D - 4382.97/D \\ &= 593.51 + 1.80(35) + 4382.97/(35) \\ &= 531\ \$/\text{MLT}. \\ \text{Lumber value} &= 531\ \$/\text{MLT} \times 0.947\ \text{MBF} = \$502.86.\end{aligned}$$

$$\begin{aligned}\text{Grade 5: } \$/\text{MLT} &= 59.72 + 8.98D + 160.11/D \\ &= 59.72 + 8.98(20) + 160.11/(20) \\ &= 247\ \$/\text{MLT}. \\ \text{Lumber value} &= 247\ \$/\text{MLT} \times 0.373\ \text{MBF} = \$92.13.\end{aligned}$$

These values can be updated to current WWPA index prices by multiplying the lumber value by the current index price and dividing the answer by the WWPA 1982 index price ($309).

2. For prices of individual lumber grades, the board-foot lumber volumes must be proportioned into the various lumber grades by use of the percentages by grade and diameter given in appendix 2. Current prices for the lumber grades can be applied to these volumes and then summed.

Example 2. Direct product estimations.

Sample logs (old growth):

Number of logs	Net cubic scale (Cubic feet)
1	100
20	1,500

Lumber volume can be predicted from the equations in the caption of figure 7.

For one log:

$$\begin{aligned}\text{Lumber volume (BF)} &= 18.541(\text{number of logs}) + 7.835(\text{net cubic scale}) \\ &= 18.541(1) + 7.835(100) \\ &= 802\ \text{BF of lumber.}\end{aligned}$$

For more than one log:

$$\begin{aligned}\text{Lumber volume (BF)} &= 18.541(\text{number of logs}) + 7.835(\text{net cubic scale}) \\ &= 18.541(20) + 7.835(1{,}500) \\ &= 12{,}123\ \text{BF of lumber.}\end{aligned}$$

Lumber value can also be predicted directly from net cubic scale by use of the direct product estimator equations from figure 8.

Metric Equivalents

1 inch = 2.54 centimeters
1 foot = 0.3048 meter
1 cubic foot = 0.02832 cubic meter

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Appendix 1

WWPA December 1982 quarterly price index list by lumber grade and size:

Thickness and grade	Price ($/MBF)
4/4, 5/4, 6/4:	
B and Better Select	1,069.74
C Select	1,069.74
D Select	972.73
Moulding	631.41
Factory Selects and 3 Clear	406.86
5/4 and 6/4:	
1 Shop	470.49
2 Shop	390.57
3 Shop	279.64
Shop Out	150.86
4/4:	
2 Shop	207.36
3 Shop	207.36
2-inch:	
No. 2 and Better or Standard and Better	175.65
No. 3 or Utility	118.64
Economy	77.34
1-inch:	
3 Common and Better	189.65
4 Common	106.92
5 Common	68.70

Appendix 2

Percentage of lumber volume by lumber grade for each log grade:

Diameter (Inches)	Moulding	2 Shop	3 Shop	Standard and Better	Utility and Economy
		GRADES 1 AND 2			
20	38	13	7	31	11
21	40	13	7	29	11
22	42	13	7	27	11
23	44	13	7	25	11
24	46	13	7	23	11
25	47	13	7	22	11
26-29	50	14	7	19	10
30-33	54	14	7	15	10
34-37	58	14	7	11	10
38-41	61	14	7	8	10
42-45	63	14	7	6	10
46-49	65	14	7	4	10
		GRADE 3			
15	12	9	11	52	16
16	14	11	11	49	15
17	16	13	12	46	13
18	17	15	12	44	12
19	19	17	11	42	11
20	21	18	11	40	10
21	22	20	11	37	10
22	23	22	11	35	9
23	24	23	12	32	9
24	26	24	11	30	9
25	27	25	11	29	8
26-29	30	28	11	23	8
30-33	33	31	10	18	8
34-37	36	34	10	12	8
38-41	38	36	9	8	8
42-45	40	39	9	4	8

GRADE 5

6	0	0	30	62	40
7	0	0	4	61	38
8	0	0	5	59	37
9	0	2	5	57	36
10	1	3	6	55	35
11	2	4	7	53	34
12	2	6	8	52	32
13	3	7	9	50	31
14	4	9	9	48	30
15	4	11	10	46	29
16	5	12	11	45	27
17	6	13	11	44	26
18	6	15	12	42	25
19	7	16	13	40	24
20	8	18	13	39	22
21	8	20	14	37	21
22	9	21	15	35	20
23	10	22	16	33	19
24	10	24	17	31	18
25	11	25	18	30	16
26-29	12	30	20	25	13
30-33	15	36	23	18	8
34-37	18	42	26	11	4
39-41	20	47	28	5	0

YOUNG GROWTH

6	3	1	3	46	47
7	2	0	2	54	51
8	1	0	3	60	36
9	1	0	3	65	32
10	0	0	3	68	29
11	0	1	3	69	27
12	2	1	3	70	24
13	1	3	3	70	23
14	4	3	3	69	21
15	5	4	4	67	20
16	7	6	3	65	19
17	8	8	4	62	18
18	10	10	4	59	17
19	11	13	5	55	16
20	17	13	4	51	15
21	16	17	5	47	15
22	20	18	5	43	14

Equations for the cumulative percent volumes by log grade and lumber grade:

		R^2	MSE
Grades 1 and 2:			
Utility and Economy	$= 0.092 + 0.346(1/D)$	0.010	0.0049
Standard and Better	$= -0.059 + 9.618(1/D)$	0.577	0.0062
3 Shop	$= 0.005 + 9.759(1/D)$	0.378	0.0144
2 Shop	$= 0.155 + 9.358(1/D)$	0.310	0.0219
Selects and Moulding	= 1.0 − 2 Shop		
Grade 3:			
Utility and Economy	$= 0.149 - 4.300(1/D) + 66.942(1/D^2)$	0.341	0.0167
Standard and Better	$= -0.257 + 18.343(1/D) - 63.851(1/D^2)$	0.852	0.0073
3 Shop	$= -0.218 + 20.972(1/D) - 87.320(1/D^2)$	0.727	0.0159
2 Shop	$= 0.385 + 10.121(1/D) - 41.352(1/D^2)$	0.361	0.0180
Selects and Moulding	= 1.0 − 2 Shop		
Grade 5:			
Utility and Economy	$= 0.470 - 0.012(1/D)$	0.181	0.0610
Standard and Better	$= 1.196 - 0.029(1/D)$	0.766	0.0156
3 Shop	$= 1.179 - 0.022(1/D)$	0.669	0.0152
2 Shop	$= 1.054 - 0.007(1/D)$	0.320	0.0094
Selects and Moulding	= 1.0 − 2 Shop		
Young growth:			
Utility and Economy	$= 0.018 + 2.755(1/D)$	0.158	0.0603
Standard and Better	$= 2.731 - 0.073(D) - 13.541(1/D) + 32.615(1/D^2)$	0.457	0.0133
3 Shop	$= 2.642 - 0.069(D) - 12.572(1/D) + 30.123(1/D^2)$	0.496	0.0101
2 Shop	$= 1.932 - 0.037(D) - 7.533(1/D) + 18.933(1/D^2)$	0.237	0.0075
Selects and Moulding	= 1.0 − 2 Shop		

*GPO 594 - 631 (1985)

Ernst, Susan; Pong, W. Y. Lumber recovery from ponderosa pine in northern California. Res. Pap. PNW-333. Portland, OR: U.S. Department of Agriculture, Pacific Northwest Forest and Range Experiment Station; **1985.** 22 p.

Lumber recovery information from 942 logs from old- and young-growth ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) trees in northern California is presented. More than 58 percent of the lumber volume was found in 5/4 Shop, Moulding, and Select grades. About 25 percent of the total lumber volume was Moulding, and 24 percent was Standard and Better Dimension. Lumber volume recovery is presented on the basis of cubic feet and board feet. Volume recovery varied by scaling diameter but not by log grade. Value recovery and percent volume by lumber grade did vary by log grade and diameter, but no difference was found between the grade 1 and the grade 2 logs.

Keywords: Lumber yield, lumber recovery, ponderosa pine, *Pinus ponderosa*, California (northern), northern California.

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Research Paper
PNW-334
February 1985

Response of Sitka Spruce and Western Hemlock to Commercial Thinning

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Abstract

Graham, Joseph N.; Bell, John F.; Herman, Francis R. Response of Sitka spruce and western hemlock to commercial thinning. Res. Pap. PNW-334 Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 17 p.

Light commercial thinning in 100-year-old, well-stocked, mixed stands of western hemlock and Sitka spruce at Cascade Head Experimental Forest produced no consistent growth and yield responses related to thinning intensity. Mortality for all causes except windfall was generally less for thinned stands than for unthinned stands. Losses from windfall appear to be related more to location than to thinning.

Keywords: Commercial thinning, mixed stands, thinning effects, western hemlock, *Tsuga heterophylla,* Sitka spruce, *Picea sitchensis,* Oregon (Cascade Head Exp. For.), Cascade Head Exp. For.—Oregon.

Research Summary

Relatively light commercial thinning in a 100-year-old mixed stand of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) on the Cascade Head Experimental Forest near Otis, Oregon, was prescribed to preserve wind firmness of the stands, recover or forestall mortality, and concentrate potential growth on selected trees. Thinning regimes proposed removal of 15 to 25 percent of the basal area. Thinning was done between 1947 and 1951. Measurements were made between 1947 and 1964 (table 10).

While light commercial thinning produced no consistent growth and yield responses related to thinning intensity, the unthinned natural stands averaged about 30 percent more gross growth and 10 percent more net growth than commercially thinned counterparts. The difference in gross and net growth is due primarily to the greater amount of unrecovered mortality in the unthinned areas. It appears that in these century-old forests, stands with a small (less than 20 percent) component of western hemlock may not respond as well to commercial thinning as stands with a larger (more than 35 percent) component of western hemlock. Gross growth seems to be greater in stands of higher density, both thinned and unthinned. In the least dense stand, however, with about 340 square feet of basal area per acre (78 m^2/ha), gross growth was enhanced by commercial thinning.

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roduction

The very dense coastal forests of the Sitka spruce (*Picea sitchensis* (Bong.) Carr.) zone (Franklin and Dyrness 1973) in Oregon and Washington are among the most productive coniferous forests in the world (Fujimori 1971) but are characteristically very susceptible to wind damage and mortality. To study the effect of commercial thinning on growth and yield in a 100-year-old stand of the Sitka spruce-western hemlock type, nine study tracts were established between 1947 and 1951 (fig. 1). Six of these tracts were thinned to various densities. Logging was done with horses, tractors, and a combination of the two. The three remaining unthinned tracts served as controls (tables 1 and 2).

The objective of the study was to evaluate growth and yield resulting from various thinning regimes and to determine whether thinning can reduce or forestall the amount of mortality and concentrate growth potential on trees in the residual stand.

The purpose of this report is to summarize and interpret data collected between 1947 and 1964 and to provide insight into the effects of thinning on growth and yield of the Sitka spruce-western hemlock type.

Figure 1.—A 1978 view of a 120-year-old Sitka spruce-western hemlock stand commercially thinned in 1947, Cascade Head Experimental Forest, Oregon.

Table 1—Description of study tracts and sample plots

Tract and treatment 1/	Year established	Tract size		Number of plots	Plot size	Area sampled	Sampling intensity
		Acres	Hectares		--Acres--		Percent
1B(UT)	1947	15	6	4	0.1	0.4	2.7
1B(T)	1947	25	10	6	.1	.6	2.4
1E(UT)	1947	61	24.7	16	.1	1.6	2.6
1E(T)	1947	100	40.5	28	.1	2.8	2.8
3C(UT)	1948	31	12.5	10	.2	2.0	6.5
3C(T)	1948	30	12.1	7	.2	1.4	1.8
8(T)	1950	7	2.8	8	.1	.8	11.4
9A(T)	1949	36	14.6	20	.1	2.0	2.3
10F(T)	1951	76	30.8	11	.2	2.2	2.9
Total unthinned		107	43.3	30	--	4.0	3.7
Total thinned		374	151.4	80	--	9.8	2.6
Total all plots		381	154.2	110	--	13.8	2.9

1/ UT = unthinned, T = thinned.

Table 2—Percent removal, proposed and accomplished, by stems per acre and cubic-foot volume to a 4-inch top and board-foot volume to a 6-inch top, by tract and thinning regimes (1947-51)

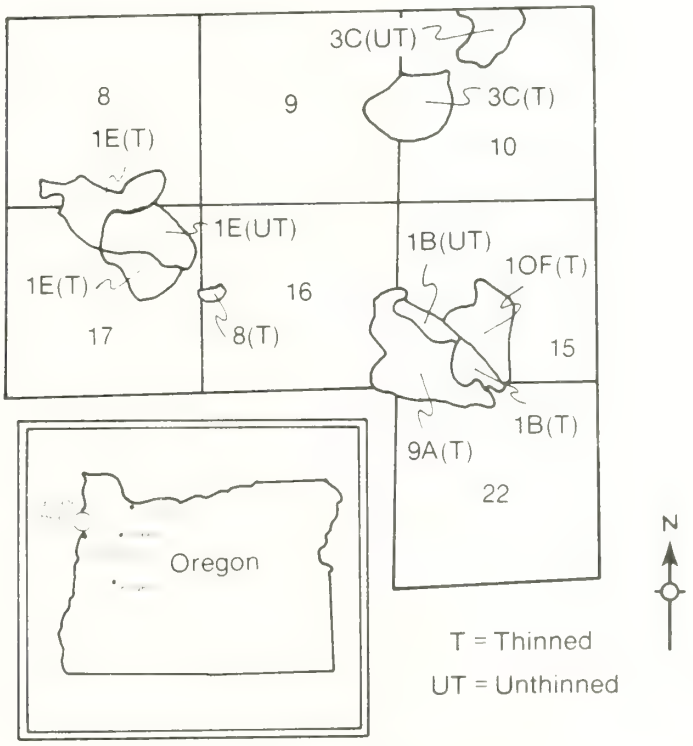
Tract and treatment 1/	Proposed removal	Removed			
		Stems per acre	Basal area per acre	Volume	
				Cubic feet	Board feet
		Percent			
1B(UT)	0	0	0	0	0
1B(T)	15	31.7	21.1	20.8	18.9
1E(UT)	0	0	0	0	0
1E(T)	25	30.7	22.1	24.7	23.5
3C(UT)	0	0	0	0	0
3C(T)	20	34.9	23.0	21.9	20.5
8(T)	25	17.3	15.9	15.9	14.8
9A(T)	15	23.6	13.3	12.1	10.9
10F(T)	20	33.5	21.2	20.8	18.6

1/ UT = unthinned; T = thinned.

udy Area

The study tracts are located in the Cascade Head Experimental Forest on the west slope of the Coast Ranges near Otis, Oregon (fig. 2).

The Cascade Head Experimental Forest was established by the USDA Forest Service in 1934 and has been maintained by the Pacific Northwest Forest and Range Experiment Station in cooperation with the Siuslaw National Forest.



Township 6 South, Range 10 West of the Willamette Meridian

Figure 2.—Approximate location and relative size of study tracts

mate

The climate is typical of the coastal fog belt and is characterized by mild temperatures, high humidity, frequent rain, and summer fog. Annual rainfall for the study area is approximately 90 inches (230 cm) and occurs primarily between October and April. The maritime influence of the Pacific Ocean results in a long growing season, with favorable moisture conditions the year around and only slight seasonal and diurnal fluctuations in temperature from the 50 °F (10 °C) mean (Madison 1957).

Site Index

Site index of the study stands could not be determined directly from the existing data. Studies conducted in similar nearby stands (Smith and others 1984) reveal an average site index of about 140 for western hemlock (Barnes 1962). For the purposes of this study the area is assumed to be of uniform site quality.

The Stand

The well-stocked, even-aged stands of Sitka spruce and western hemlock on the Cascade Head Experimental Forest are thought to have originated about 1850 following a severe forest fire.

Species composition and size distribution within the stands are indicated in tables 3 through 7, which summarize several basic stand parameters and provide insights into the similarities and dissimilarities of study tracts.

Table 3—Stand composition (western hemlock, Sitka spruce and Douglas-fir) based on stems per acre, before and after thinning and in 1964

Tract, treatment and species 1/	Before thinning	After thinning (1947-51)	In 1964
	----------Percent----------		
1B(UT):			
Western hemlock	75.4	--	76.0
Sitka spruce	23.1	--	22.0
Douglas-fir	1.5	--	2.0
1B(T):			
Western hemlock	86.5	83.1	84.1
Sitka spruce	13.5	16.9	15.9
Douglas-fir	0	0	0
1E(UT):			
Western hemlock	35.0	--	35.1
Sitka spruce	53.0	--	53.0
Douglas-fir	12.0	--	11.9
1E(T)			
Western hemlock	33.7	29.7	29.2
Sitka spruce	56.1	60.8	62.6
Douglas-fir	10.2	9.5	8.2
3C(UT):			
Western hemlock	56.4	--	58.5
Sitka spruce	32.7	--	32.1
Douglas-fir	10.9	--	9.4
3C(T):			
Western hemlock	60.6	63.5	60.9
Sitka spruce	38.1	36.5	39.1
Douglas-fir	1.3	0	0
8(T):			
Western hemlock	47.4	43.6	44.8
Sitka spruce	43.6	45.5	44.8
Douglas-fir	9.0	10.9	10.4
9A(T):			
Western hemlock	77.6	76.6	74.6
Sitka spruce	15.5	17.0	18.7
Douglas-fir	6.9	6.4	6.7
10F(T):			
Western hemlock	80.0	79.8	79.6
Sitka spruce	18.0	18.0	18.1
Douglas-fir	2.0	2.2	2.3

1/ UT = unthinned, T = thinned.

Table 4—Average number of stems 2 inches (5.1 cm) d.b.h. and larger per acre and per hectare before and after thinning and in 1964

Tract and treatment 1/	Stems before thinning		Stems after thinning (1947-51)		Stems in 1964	
	Per acre	Per hectare	Per acre	Per hectare	Per acre	Per hectare
1B(UT)	162.5	401.5	--	--	125.0	308.9
1B(T)	173.3	428.2	118.3	292.3	105.0	259.5
1E(UT)	114.4	282.7	--	--	105.0	259.5
1E(T)	119.6	295.5	83.5	206.3	69.6	172.0
3C(UT)	116.8	288.6	--	--	101.8	251.5
3C(T)	114.3	282.4	73.2	180.9	62.1	153.4
8(T)	166.3	410.9	139.2	344.0	131.3	324.4
9A(T)	145.5	359.5	117.0	289.1	104.5	258.2
10F(T)	184.5	455.9	126.1	311.6	118.2	292.1

1/ UT = unthinned, T = thinned.

Table 5—Average quadratic mean diameter, by tract and species, before and after thinning and in 1964

Tract, treatment and species 1/	Diameter before thinning		Diameter after thinning (1947-51)		Diameter in 1964	
	Inches	Centimeters	Inches	Centimeters	Inches	Centimeters
1B(UT):						
Western hemlock	18.6	47.2	--	--	20.4	51.8
Sitka spruce	26.4	67.1	--	--	30.9	78.5
Douglas-fir	29.1	73.9	--	--	31.2	79.2
1B(T):						
Western hemlock	18.8	47.8	20.0	50.8	22.1	56.1
Sitka spruce	24.8	63.0	25.8	65.5	29.4	74.7
Douglas-fir	--	--	--	--	--	--
1E(UT):						
Western hemlock	15.8	40.1	--	--	17.8	45.2
Sitka spruce	28.5	72.4	--	--	31.6	80.3
Douglas-fir	23.0	58.4	--	--	24.8	63.0
1E(T):						
Western hemlock	16.2	41.1	16.0	40.6	18.1	46.0
Sitka spruce	23.9	60.7	24.9	63.2	27.7	70.4
Douglas-fir	24.4	62.0	24.8	63.0	28.4	72.1
3C(UT):						
Western hemlock	18.3	46.5	--	--	20.1	51.1
Sitka spruce	28.4	72.1	--	--	31.9	81.0
Douglas-fir	24.4	62.0	--	--	26.4	67.1
3C(T):						
Western hemlock	19.1	48.5	21.2	53.8	24.9	63.2
Sitka spruce	27.8	70.6	31.6	80.3	35.0	88.9
Douglas-fir	50.9	29.3	--	--	--	--
8(T):						
Western hemlock	19.3	49.0	18.7	47.5	21.0	53.3
Sitka spruce	25.4	64.5	26.2	66.5	27.7	70.4
Douglas-fir	21.5	54.6	21.5	54.6	22.8	57.9
9A(T):						
Western hemlock	19.4	49.3	20.7	52.6	21.7	55.1
Sitka spruce	28.9	73.4	29.7	75.4	32.7	83.1
Douglas-fir	22.5	57.2	22.9	58.2	25.9	65.8
10F(T):						
Western hemlock	17.9	45.5	19.3	49.0	20.9	53.1
Sitka Spruce	24.2	61.5	26.4	67.1	29.0	73.7
Douglas-fir	22.5	57.2	24.1	61.2	25.4	64.5

1/ UT= unthinned, T = thinned.

Table 6—Average basal area per acre and per hectare, by tract, before and after thinning and in 1964, and amount and percent removed

Tract and treatment 1/	Basal area before thinning		Basal area after thinning (1947-51)		Basal area in 1964		Basal area removed		Percent of initial basal area removed
	ft^2/acre	m^2/ha	ft^2/acre	m^2/ha	ft^2/acre	m^2/ha	ft^2/acre	m^2/ha	
1B(UT)	384.7	88.3	--	--	372.7	85.6	--	--	--
1B(T)	365.5	83.9	288.1	66.1	314.1	72.1	77.4	17.8	21.1
1E(UT)	363.7	83.5	--	--	408.6	93.8	—	—	--
1E(T)	307.2	70.5	233.2	53.5	245.1	56.3	74.0	17.0	24.1
3C(UT)	329.6	75.7	--	--	350.0	80.3	—	—	--
3C(T)	342.0	78.5	254.3	58.4	290.3	66.6	77.7	17.8	22.7
8(T)	452.0	103.8	380.5	87.3	425.9	97.8	71.8	16.5	15.9
9A(T)	359.0	82.4	315.6	72.5	339.8	78.0	43.4	10.0	12.1
10F(T)	373.4	85.7	294.3	67.6	331.3	76.1	79.1	18.2	21.2

1/ UT = unthinned, T = thinned.

Table 7—Standing volume, by tract, before and after thinning and in 1964, in cubic feet to a 4-inch top and Scribner rule to a 6-inch top

Tract and treatment 1/	Volume before thinning		Volume after thinning (1947-51)		Volume in 1964	
	ft^3/acre	MBF/acre	ft^3/acre	MBF/acre	ft^3/acre	MBF/acre
1B(UT)	20,020	121.6	--	--	22,399	137.3
1B(T)	19,996	117.3	15,830	95.1	18,619	114.6
1E(UT)	18,841	119.2	--	--	23,147	150.3
1E(T)	15,577	93.7	11,731	71.7	13,606	84.6
3C(UT)	16,024	102.5	--	--	18,130	118.2
3C(T)	18,562	114.7	14,493	91.2	16,635	106.6
8(T)	22,865	142.1	19,240	121.0	22,594	143.7
9A(T)	20,389	123.1	17,921	109.7	20,397	126.6
10F(T)	21,916	125.5	17,356	102.2	19,956	120.9

1/ UT = unthinned, T = thinned.

Treatments

Between 1947 and 1951, 110 permanent sample plots were established in nine study tracts—three control and six to be treated by thinning.

The original tracts consisted of three pairs, one unthinned control and one treatment, without replication (1B unthinned and 1B thinned, 1E unthinned and 1E thinned, 3C unthinned and 3C thinned). Tracts 8, 9A and 10F were added to the study (see table 1). These three treatment tracts are not paired with control tracts, but, as figure 3 indicates, they are adjacent to or close to the other control tracts.

On the six treatment tracts almost 400 acres (160 hectares) were commercially thinned under regimes that proposed removing 15 to 25 percent of the total basal area (tables 8-12).

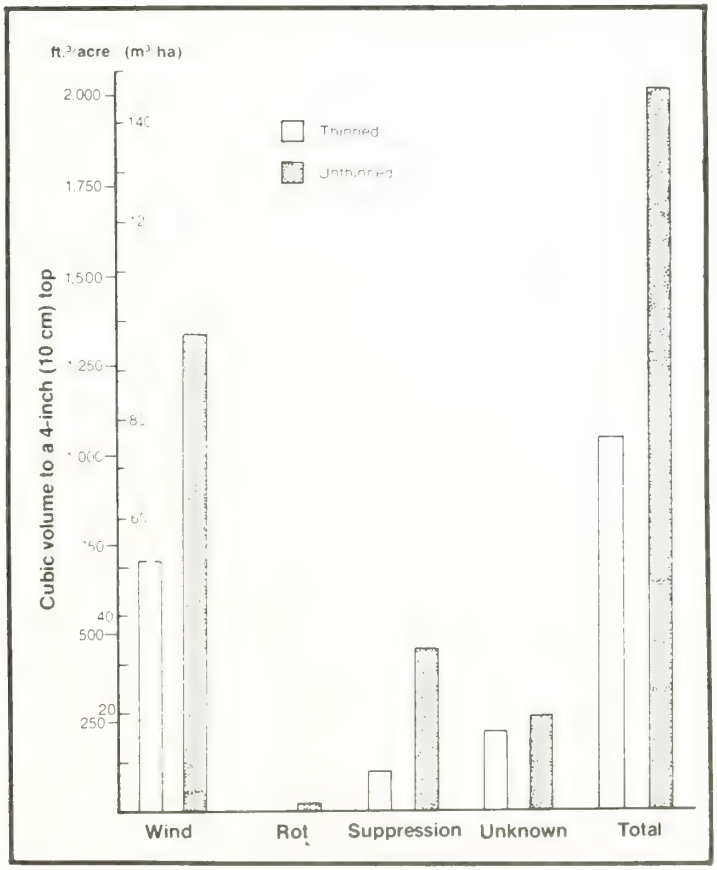


Figure 3.—Comparison of gross growth to initial basal area, by tract and treatment.

Table 8—Average trees per acre, basal area, and diameter of initial stand, and amount and percent removed from thinned tracts, by species, in English units

Tract and species	Initial stand			Amount removed			Percent removed		
	Trees/ acre	Basal area	Diameter b.h.	Trees/ acre	Basal area	Diameter b.h.	Trees/ acre	Basal area	d/D 1/
		ft^2/acre	in		ft^2/acre	in		ft^2/acre	
1B:									
Western hemlock	150.0	287.6	18.7	51.7	71.6	15.9	34.5	24.9	.850
Sitka spruce	23.3	77.8	24.8	3.3	5.6	17.6	14.2	7.2	.712
Douglas-fir	0	0	--	--	--	--	--	--	--
	173.3	365.4	19.7	55.0	77.2	16.0	31.7	21.1	.816
1E:									
Western hemlock	40.4	57.8	16.2	15.7	24.1	16.8	38.9	41.7	1.036
Sitka spruce	67.1	08.7	23.9	16.8	39.2	20.7	25.0	18.8	.866
Douglas-fir	12.5	40.6	24.4	4.3	4.6	23.0	34.4	11.3	.943
	120.0	307.1	21.7	36.9	67.9	19.4	30.8	22.1	.895
3C:									
Western hemlock	69.3	38.2	19.1	22.1	22.9	13.8	31.9	16.6	.721
Sitka spruce	43.6	83.8	27.8	16.4	36.0	20.1	37.6	19.6	.722
Douglas-fir	1.4	19.8	50.9	1.4	19.8	50.9	100.0	100.0	1.000
	114.3	34.8	23.4	39.9	78.7	19.1	34.9	23.0	.315
8:									
Western hemlock	78.8	159.3	19.3	16.3	40.4	21.3	20.7	25.4	1.104
Sitka spruce	72.5	255.3	25.4	12.5	31.5	21.5	17.2	12.3	.846
Douglas-fir	15.0	37.7	21.5	0	0	--	0	0	--
	66.3	452.3	22.3	28.8	71.9	21.4	17.3	15.9	.960
9A:									
Western hemlock	114.0	233.0	19.4	30.5	38.7	15.3	26.8	16.6	.788
Sitka spruce	22.0	100.0	28.9	2.5	5.9	20.9	11.4	5.9	.723
Douglas-fir	10.0	28.0	22.5	1.5	3.3	20.2	15.0	11.9	.896
	146.0	361.0	21.3	34.5	47.9	16.0	24.4	13.3	.751
10F:									
Western hemlock	147.7	257.3	17.9	50.9	60.4	14.8	34.5	23.5	.825
Sitka spruce	33.2	106.0	24.2	10.0	17.3	18.1	30.1	16.8	.747
Douglas-fir	3.6	10.0	22.5	0.9	1.4	16.8	25.0	14.0	.746
	184.5	373.3	19.3	61.8	79.6	14.8	33.5	21.3	.770

1/ d = quadratic mean diameter of trees thinned, D = quadratic mean diameter of all trees prior to thinning.

Table 9—Average trees per acre, basal area, and diameter in initial stand, and amount and percent removed from thinned tracts, by species, in metric units

Tract and species	Initial stand			Amount removed			Percent removed		
	Trees/ hectare	Basal area	Diameter b.h.	Trees/ hectare	Basal area	Diameter b.h.	Trees/ hectare	Basal area	d/D 1/
		m^2/ha	cm		m^2/ha	cm		m^2/ha	
1B:									
Western hemlock	371	26.7	47.5	128	6.7	40.7	34.5	24.9	.850
Sitka spruce	58	7.2	63.6	8	.5	44.7	14.2	7.2	.712
Douglas-fir	0	0	0	0	0	0	--	--	--
	429	33.9	50.0	136	7.2	40.6	31.7	21.1	.816
1E:									
Western hemlock	100	5.4	41.1	39	2.2	42.7	38.9	41.7	1.036
Sitka spruce	166	19.4	60.7	42	3.6	52.6	25.0	18.8	.866
Douglas-fir	31	3.8	62.0	11	.4	58.4	34.4	11.3	.943
	297	28.6	55.1	92	6.2	49.3	30.8	22.1	.895
3C:									
Western hemlock	171	12.8	48.5	55	2.1	35.1	31.9	16.6	.721
Sitka spruce	108	17.1	70.6	41	3.3	51.1	37.6	19.6	.722
Douglas-fir	3	1.8	29.3	3	1.8	129.3	00.0	100.0	1.000
	282	31.7	59.4	99	7.2	48.5	34.9	23.0	.315
1B:									
Western hemlock	195	14.8	49.0	40	3.8	54.1	20.7	25.4	1.104
Sitka spruce	179	23.7	64.5	31	2.9	54.6	17.2	12.3	.846
Douglas-fir	37	3.5	54.6	0	0	0	0	0	
	411	42.0	59.4	71	6.7	54.4	17.3	15.9	.960
1E:									
Western hemlock	282	21.6	49.3	75	3.6	38.9	26.8	16.6	.788
Sitka spruce	54	9.3	73.4	6	.5	53.1	11.4	5.9	.723
Douglas-fir	25	2.6	57.2	4	.3	51.3	15.0	11.9	.896
	361	33.5	56.6	85	4.4	40.6	23.6	13.3	.751
3C:									
Western hemlock	365	23.9	45.5	126	5.6	37.6	34.5	23.5	.825
Sitka spruce	82	9.8	61.5	25	1.6	46.0	30.1	16.8	.747
Douglas-fir	9	.9	57.2	2	0.1	42.7	25.0	14.0	.746
	456	34.6	54.1	153	7.3	37.6	33.5	21.2	.770

1/ d = quadratic mean diameter of trees thinned, D = quadratic mean diameter of all trees prior to thinning.

Table 10—Schedule of measurements (M) and thinning (T)

Tract and treatment 1/	Proposed removal	1947	1948	1949	1950	1951	1952	1954	1956	1964
	Percent									
1B(UT)	0	M						M		M
1B(T)	15	M	T					M		M
1E(UT)	0	M							M	M
1E(T)	25	M	T	T 2/					TM 3/	M
3C(UT)	0		M						M	M
3C(T)	20		MT	T 2/					TM	M
8(T)	25				MT					M
9A(T)	15			MT	T	T 2/				M
10F(T)	20					M	T			M

1/ UT = unthinned, T = thinned.

2/ Records indicate that thinning operations occurred in more than one growing season but there is no indication that they were intended to be more than a single treatment.

3/ Intermediate cuttings to recover mortality occurred prior to measurement.

Table 11—Cubic volume removed from thinned tracts, by species, to a 4-inch (10.2 cm) top

Tract	Western hemlock		Sitka spruce		Douglas-fir		All species	
	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha
1B	3,866.2	270.5	299.4	20.9	--	--	4,165.6	291.5
1E	1,217.1	85.2	2,013.4	140.9	615.0	43.0	3,845.5	269.1
3C	1,137.5	79.6	2,003.1	140.2	928.0	64.9	4,068.6	284.7
8	1,955.6	136.8	1,669.4	116.8	--	--	3,625.0	253.6
9A	2,064.9	144.5	301.4	21.1	101.4	7.1	2,467.7	172.7
10F	3,450.6	241.4	1,039.4	72.7	70.9	5.0	4,559.9	319.1

Table 12—Cubic volume per acre and per hectare, by tract, before and after thinning, and amount removed by thinning and mortality, to a 4-inch (10.2-cm) top

Tract 1/	Before thinning		Removed by thinning (1947-51)		After thinning		Lost to mortality		Volume in 1964	
	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha
1B(UT)	20,020	1,401	--	--	--	--	4,157	291	22,399	1,567
1B(T)	19,996	1,399	4,166	292	15,830	1,108	1,242	87	18,619	1,303
1E(UT)	18,481	1,293	--	--	--	--	815	57	23,147	1,620
1E(T)	15,577	1,090	3,845	269	11,732	821	1,725	121	13,606	952
3C(UT)	16,024	1,121	--	--	--	--	1,366	96	18,130	1,269
3C(T)	18,562	1,299	4,069	285	14,494	1,014	1,277	89	16,635	1,164
8(T)	22,865	1,600	3,625	254	19,240	1,346	689	48	22,954	1,581
9A(T)	20,389	1,427	2,468	173	17,921	1,254	1,277	89	20,397	1,427
10F(T)	21,916	1,533	4,560	319	17,356	1,214	414	29	19,956	1,396

1/ UT = unthinned, T = thinned.

Thinning

Examination of stand table data suggests that the thinnings were a combination of low- and crown-methods, although some of the entries were termed sanitation and salvage cuttings. These thinnings were relatively light to preserve the wind firmness of the characteristically shallow-rooted trees. The decision to thin lightly may also have been based on the presumption that heavier thinning would have reduced growth on residual trees to the point where it could not compensate for potential lost growth when trees were cut.

The main objectives of thinning were to recover or forestall mortality and concentrate potential growth on the better trees.

Measurements

From the existing field records,[1] it appears that the initial measurements were made when the study tracts were established. At that time, diameter at breast height was measured on all plot trees. Some trees were measured for total height, but none were bored to determine age. Subsequent periodic measurements and mortality observations were taken for growth comparison (tables 10, 12 and 13).

Table 13—Summary of growing seasons between measurements by tract and treatment

Tract and treatment	First period	Second period	Total observation period
		Growing seasons	
1B, unthinned	7	11	18
1B, thinned	7	11	18
1E, unthinned	9	9	18
1E, thinned	9	9	18
3C, unthinned	7	9	16
3C, thinned	7	9	16
8, thinned	15	-	15
9A, thinned	16	-	16
10F,thinned	13	-	13

Methods

Volume Computation

In this study volume estimates utilize tarif-volume equations computed with British Columbia volume-equation coefficients for immature coastal western hemlock, Sitka spruce, and Douglas-fir (Brackett 1973).

Only a portion of the sample trees was measured for total height at any one measurement. The same trees were not always remeasured. On some trees height measurements were inconsistent, indicating negative or highly fluctuating height growth.

[1] Data on file at Forestry Sciences Laboratory, Corvallis, Oregon, under study W-26, dated 1947, by Robert H. Ruth.

Therefore, we computed tarif access numbers only from trees measured more than once and showing increased height growth. This procedure was necessary to eliminate the inconsistencies in stand growth found in the preliminary analyses. These data are summarized in table 14. Generally, the annual tarif increments appear to correspond well with the findings of Reukema and Pienaar (1973) and Graham (1978). In most instances, these modest tarif increments should result in conservative estimates of volume growth.

Table 14—Average tarif numbers by tract, species, and measurement period

Tract, treatment, and species 1/	Average tarif number 2/			
	First measurement	Second measurement	Third measurement	Average annual tarif increment
1B(UT):				
Western hemlock	49.6	54.1	57.9	.46
Sitka spruce	49.6	51.9	55.7	.34
Douglas-fir	40.1	41.8	43.0	.16
1B(T):				
Western hemlock	52.4	53.6	55.8	.19
Sitka spruce	51.0	51.9	55.5	.25
Douglas-fir	42.2	43.8	45.2	.17
1E(UT):				
Western hemlock	43.0	47.6	49.7	.37
Sitka spruce	49.7	52.7	54.9	.29
Douglas-fir	40.1	42.5	43.0	.16
1E(T):				
Western hemlock	44.7	47.1	49.3	.26
Sitka spruce	47.3	49.7	51.0	.21
Douglas-fir	42.2	43.8	45.2	.17
3C(UT):				
Western hemlock	44.9	46.6	47.8	.18
Sitka spruce	47.8	49.1	50.1	.14
Douglas-fir	40.1	42.5	43.0	.18
3C(T):				
Western hemlock	46.3	37.9	49.2	.18
Sitka spruce	52.0	53.2	53.3	.08
Douglas-fir	42.2	43.8	45.2	.17
8(T):				
Western hemlock	45.9	48.5	--	.17
Sitka spruce	50.2	51.9	--	.11
Douglas-fir	37.9	40.6	--	.18
9A(T):				
Western hemlock	53.8	56.0	--	.14
Sitka spruce	55.6	58.4	--	.18
Douglas-fir	46.3	49.2	--	.18
10F(T):				
Western hemlock	56.3	56.9	--	.05
Sitka spruce	55.9	57.0	--	.08
Douglas-fir	49.1	50.4	--	.10

1/ UT = unthinned, T = thinned.

2/ Tarif number as defined by the Washington State Department of Natural Resources Tarif Tables (Bracket 1973)

Volume Growth

A summary of average annual volume growth is presented in table 15. Comparing averages for the control and treatment areas reveals that the natural stands in this study average about 30 percent more gross growth and about 10 percent more net growth than their commercially thinned counterparts. This difference in gross and net growth is due primarily to the greater amount of unrecovered mortality in the control areas.

Tract 3C(T) and its control, Tract 3C(UT), are the only paired tracts in which gross and net volume growth are essentially equal (table 15). These tracts are also the only two in which western hemlock was not reduced in both basal area and number of stems per acre.

Table 15—Periodic annual increment, in cubic volume of trees to a 4-inch (10.2-cm) top and Scribner board-foot volume to a 6-inch top

Tract and treatment 1/	Cubic volume				Scribner rule	
	Gross		Net		Gross	Net
	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha	board ft/acre	
1B (UT)	363	25.4	132	9.2	2,225	809
1B (T)	224	15.7	155	10.8	1,379	954
1E (UT)	304	21.3	259	18.1	1,974	1,681
1E (T)	200	14.0	104	7.3	1,288	670
3C (UT)	217	15.2	132	9.2	1,415	861
3C (T)	211	14.8	134	9.4	1,399	887
8 (T)	270	18.9	224	15.7	1,717	1,424
9A (T)	235	16.4	155	10.8	1,459	962
10F(T)	232	16.2	200	14.0	1,405	1,211
Averages						
Unthinned	295	20.6	174	12.2	1,871	1,117
Thinned	229	16.0	162	11.3	1,441	1,018

1/ UT = unthinned, T = thinned.

The paired control and treatment areas, tracts IE(UT) and IE(T) had the highest and lowest periodic annual increment—net cubic volume (table 15). These two stands also have the smallest western hemlock component (tables 3 and 16) of all stands in the study. These data seem to suggest that in century-old stands of this cover type, those with a smaller component of western hemlock may not respond as well to commercial thinning. Perhaps this response is merely a reflection of the silvics of this species.

Generally, gross growth is greater in higher density stands, both thinned and unthinned (fig. 3).

Computation of mean annual increment (MAI) for these stands was not possible with the existing data base.

Table 16—Percentage of western hemlock in all tracts, by basal area at initial measurement (1947-51) and final measurement in 1964

Tract and treatment 1/	Initial measurement	Final measurement
	-----Percent----	
1B(UT)	59.8	58.0
1B(T)	78.7	75.0
1E(UT)	15.0	15.6
1E(T)	18.8	15.1
3C(UT)	36.4	37.6
3C(T)	40.4	44.1
8(T)	35.2	33.1
9A(T)	63.8	59.0
10F(T)	68.9	67.6

1/ UT = unthinned, T = thinned.

Mortality

Losses in growth and growing stock to natural or human-caused mortality (table 17) are difficult to assess. Each stand presents a unique situation of interrelated mortality factors (wind, decay, age, and logging damage) whose complexity is far beyond the analysis presented here. Some observations can be made by comparing thinned and control tracts, but exceptions are found within individual treatment areas.

Table 17—Volume of mortality in trees to a 4-inch (10.2-cm) top, to 1964, by cause, excluding damage caused by thinning

Tract and treatment 1/	Thinned (1947-51)		Wind		Rot		Suppression		Unknown		Total mortality	
	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha	ft^3/acre	m^3/ha
1B(UT)	0	0	2,900.0	202.9	0	0	822.7	57.6	433.4	30.3	4,156.1	290.8
1B(T)	4,165.6	291.5	468.9	32.8	0	0	106.4	7.4	666.8	46.7	1,242.1	86.9
1E(UT)	0	0	187.0	13.1	0	0	304.8	21.3	323.6	22.6	805.4	56.4
1E(T)	3,845.5	269.1	1,370.6	95.9	0	0	161.8	11.3	191.1	13.4	1,724.5	120.7
3C(UT)	0	0	929.1	65.0	45.4	3.2	291.1	20.4	87.5	6.1	1,353.1	94.0
3C(T)	4,068.6	284.7	887.4	62.1	0	0	0.8	0.1	339.1	23.7	1,227.3	85.9
8(T)	3,625.0	253.6	528.5	37.0	0	0	101.5	7.1	59.2	4.1	689.2	48.2
9A(T)	2,467.7	172.7	822.8	57.6	0	0	326.8	22.9	128.0	9.0	1,277.4	89.4
10F(T)	4,559.9	319.1	359.5	25.2	0	0	47.1	3.3	7.3	0.5	413.9	29.0
Averages												
Unthinned	0	0	1,338.7	93.7	5.1	1.1	472.8	33.1	261.5	18.3	2,078.1	145.4
Thinned	3,788.7	265.1	739.3	51.7	0	0	124.1	8.7	231.9	16.2	1,095.3	76.6

1/ UT = unthinned, T = thinned.

Results and Discussion

Light commercial thinning in century-old stands of Sitka spruce and western hemlock produced no consistent growth and yield responses related to thinning intensity. It appears that stands with a hemlock component larger than 35 percent respond best to commercial thinning.

The effect of logging operations on mortality is difficult to discern. Although mortality due to logging damage was listed as a category for the study, no mortality was directly attributed to this factor. In the thinned stands, some of the windthrow losses may have been related to logging activity.

A closer examination of the windthrow losses (table 17) reveals that the control areas have by far the greatest range and variation with respect to this cause of mortality. The windthrow losses of tract 10F may tend to distort the results. It may be that this tract, which suffered the greatest losses to the windstorms of December 4, 1951, Columbus Day 1962, and others, may have been particularly susceptible, because of some combination of predisposing factors. All windthrow losses in tract 1B(UT) occurred on half the plots. The adjacent, and presumably quite similar treatment area, tract 1B(T), incurred wind losses less than one-sixth that of its control, tract 1B(UT).

Generally, the unthinned control tracts had greater losses from wind and suppression. Data on average mortality, excluding thinning removals, represented in figure 4 and table 17, make it quite obvious that mortality in all categories was greater in the unthinned control tracts.

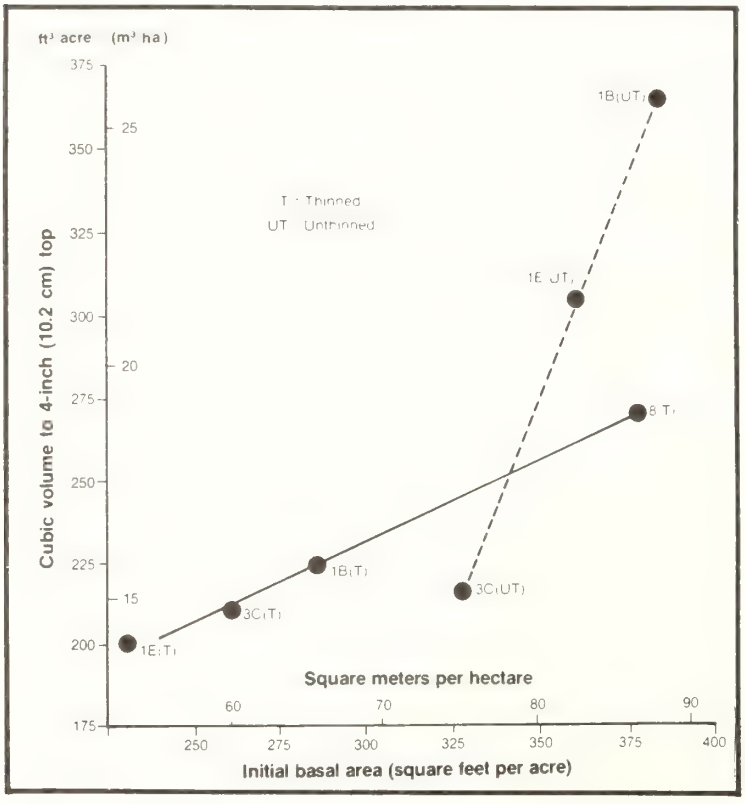


Figure 4.—Average cumulative mortality in all tracts from wind, rot, suppression, and unknown causes.

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Graham, Joseph N.; Bell, John F.; Herman, Francis R. Response of Sitka spruce and western hemlock to commercial thinning. Res. Pap. PNW-334 Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 17 p.

Light commercial thinning in 100-year-old, well-stocked, mixed stands of western hemlock and Sitka spruce at Cascade Head Experimental Forest produced no consistent growth and yield responses related to thinning intensity. Mortality for all causes except windfall was generally less for thinned stands than for unthinned stands. Losses from windfall appear to be related more to location than to thinning

Keywords: Commercial thinning, mixed stands, thinning effects, western hemlock, *Tsuga heterophylla*, Sitka spruce, *Picea sitchensis*, Oregon (Cascade Head Exp. For.), Cascade Head Exp. For.—Oregon

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Research Paper
PNW-335
March 1985

Land Ownership Patterns in the Tanana River Basin, Alaska, 1984

Willem W.S. van Hees

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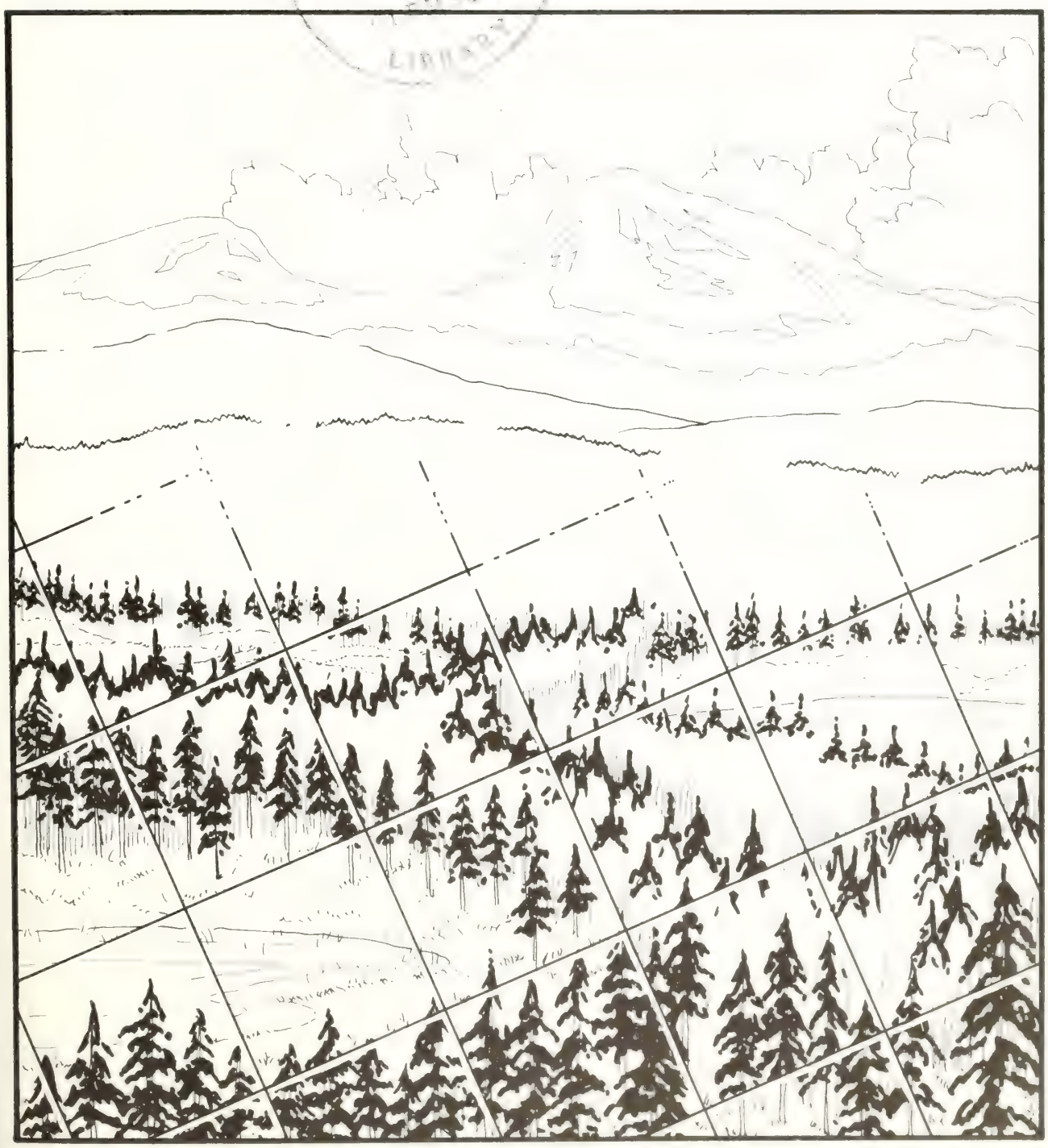

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Abstract

van Hees, Willem W.S. Land ownership patterns in the Tanana River Basin, Alaska, 1984. Res. Pap. PNW-335. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 9 p.

Aerial photo sampling coupled with information taken on the ground provided data for development of estimates of land and forest area by ownership group within the boundaries of the 1971-75 Tanana River Basin timber inventory unit, Alaska. Area of privately owned timberland is estimated at 280,634 acres (113 569 hectares).

Keywords: Land owners, forest surveys, Alaska (Tanana River).

Summary

This report contains results of the first study conducted to estimate the amount of land held by private and public owners within the confines of the 1971-75 Tanana inventory unit. A combination of aerial photo and ground sampling was used to arrive at the estimates. Total privately owned forest land is estimated to be 1,083,615 acres; publicly owned, 10,241,057 acres. Total privately owned and publicly owned areas, including Census and non-Census water, are estimated to be 1,514,850 and 12,133,021 acres, respectively.

Preface

Forest Inventory and Analysis (FIA) is a nationwide project of the USDA Forest Service authorized by the Forest and Rangeland Renewable Resources Research Act of 1978. Work units of the project, located at Forest Service Experiment Stations, conduct forest resource inventories throughout the 50 States. The Pacific Northwest Forest and Range Experiment Station is responsible for forest inventories in Alaska, California, Hawaii, Oregon, and Washington.

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1 Introduction
2 Objectives
2 Methods and Procedure
3 Results and Discussion
6 Terminology
8 Names of Trees
9 Metric Equivalents
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Introduction

Knowledge of natural resource ownership patterns is integral to development of policy and planning for managing the resources. In Alaska, this information is difficult to identify because ownership of land changes frequently. These changes in land status are the result of Federal legislation: the Alaska Statehood Act of 1958, Public Law 85-508; the Alaska Native Claims Settlement Act of 1971, Public Law 92-203; and the Alaska National Interest Lands Conservation Act, Public Law 96-487. Selection of land by Alaska Natives and withdrawal of wilderness areas are nearly complete, but selections by the State of Alaska will remain uncertain for the next 5-10 years.

The area to which statistics in this report apply is the 1971-75 Tanana River Basin timber inventory unit (fig. 1). Within the Tanana River Basin, changes in ownership of private land have stabilized, and the private land base will most likely not decrease in the future. Approximately 100,000 acres of land in the Delta Junction area, known as the Delta Barley Project, are owned by the State of Alaska but, as certain conditions of loan repayment and agricultural development are met, title will

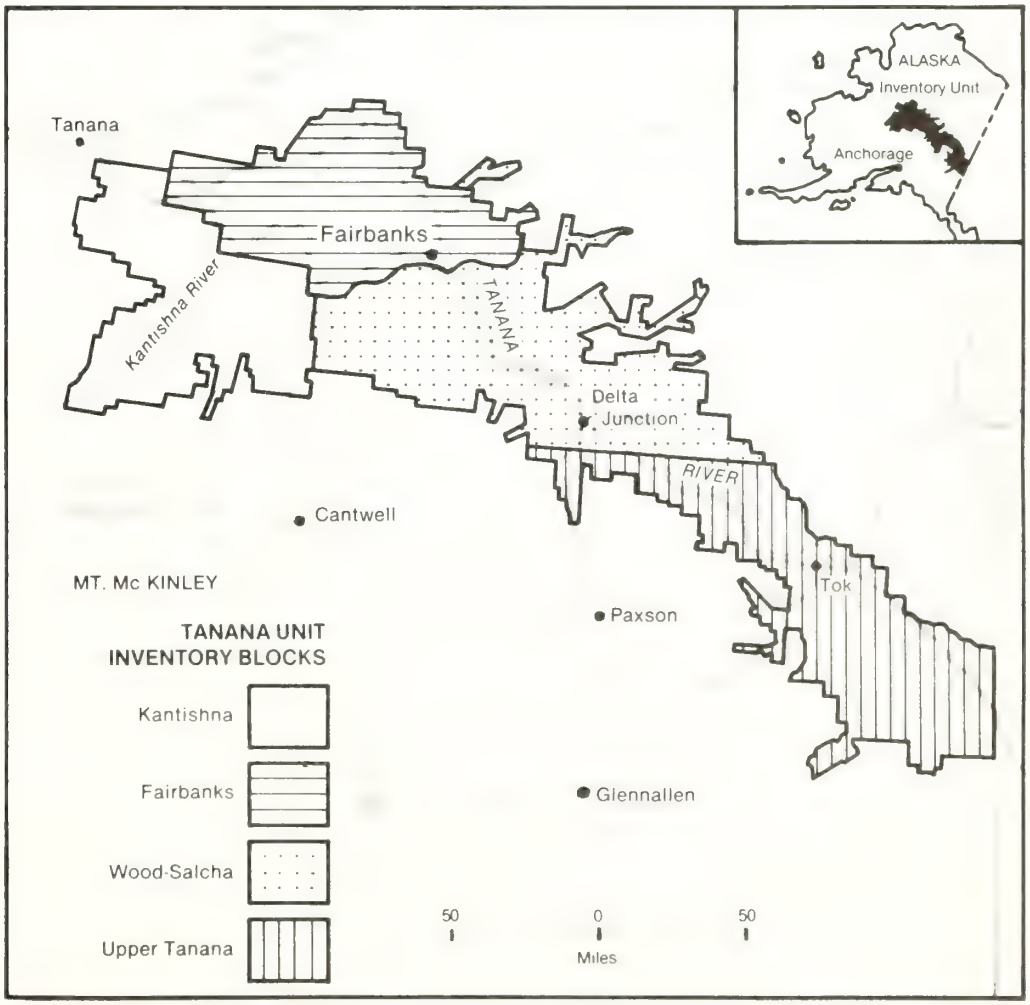

Figure 1.—Tanana inventory unit.

be conveyed to private owners. Ownership of other lands is in public hands and is still in a state of flux. This second owner category includes Federal, State, and municipal agencies. The State of Alaska will continue to make land available to private owners through its land disposal program for many years.

Just as the "public" ownership category is a combination of different public landholders, the "private" category is a combination of Alaska Natives and "other private" owners. The broad group "Alaska Native" includes general Native allotments, townsite settlements, and townsite trusteeships (wherein the land is held in trust by a Federal agency). The "other private" group includes homesteads, private airport conveyances, and mining claims. In this study Alaska Native holdings are separate from other private holdings; however, separation of the public category into its constituent parts was not possible with the procedures used.

Objectives

The main objective of this study was to produce estimates of timberland area held by private owners and by other public owners within the 1971-75 Tanana River Basin timber inventory unit. Additionally, estimates of the distribution of this acreage by forest type, stand-size class, and productivity class were desired.

Methods and Procedure

The basic procedure used to produce estimates of land area held by private and public owners was to identify private acreages first and then to subtract those figures from figures for the total Tanana River Basin inventory unit area to find the area owned by public owners.

Only the private lands for which title was conveyed to the owner were included in this study. The estimates presented in this report were current in March 1984, the date this study was begun; because land ownership changes often, they are point-in-time estimates.

The Bureau of Land Management (BLM), U.S. Department of the Interior, helped locate parcels of land that were privately owned within the Tanana unit. The BLM maintains an up-to-date file of lands for which title has been conveyed. They produced maps with a scale of 1:250,000 showing townships, ranges, and sections of privately owned lands for which title had been conveyed. Alaska Native holdings were mapped in one color and private holdings in another color.

One section, 640 acres, was the resolution used for drawing the maps. Consequently, the exact location of a particular private owner's piece of land was often impossible to determine from these maps. Exact location of a given owner's parcel can be found by examination of master survey plats, but this procedure would have been prohibitively expensive in terms of time and money. Along with the maps a computer printout was made listing exact acreages within the sections drawn on the maps. When the overlay of the Tanana timber inventory unit boundary was placed on the BLM maps, all sections containing private lands within the unit were identified. Exact acreages were then extracted from the printout.

Because exact location of privately owned lands was not achieved, precise photo interpretation of individual parcels to establish forest and land type could not be accomplished. Instead an aerial photo sample was taken as follows: After sections containing privately owned parcels of land were located and identified, photos covering those sections were identified from an aerial photo mozaic. These photos are 1:15,840 scale black and white photos; on each one three circular, 1-acre plots were interpreted to establish land and forest types.

Results of the photo interpretation were tabulated by land and forest type. From this tabulation a percent distribution of photo plots among the various land and forest type categories was developed. This percent distribution of photo plots was applied to the total privately owned acreage to categorize it by land and forest type.

Because this preliminary distribution was based on a photo sample, it was adjusted to reflect the distributions produced from the ground sample taken during the 1971-75 inventory (land and forest type were expected to change little if at all in the intervening decade). These acreages were further broken down into stand size and productivity classes by the use of proportions developed from inventory data.

Results and Discussion

Estimates in this report are subject to two types of error; procedural error and sampling error. Procedural errors were minimized by checking and rechecking each phase of the study. In some cases, there was question about the inclusion or exclusion of some sections; that is, the section drawn on the BLM map straddled the inventory unit boundary. In a few instances, only the township and range were known because of imprecise recordings by the private owner; also, because the sections containing the acreages were unknown, aerial photography for those sections could not be identified. The total acreage involved in these cases was less than 2 percent of the total area.

Sampling error attendant to the various estimates of area classes results from a less than 100-percent inventory of the private lands on aerial photos and on the ground. If photo interpretation were exact (that is, if there were no question about the classification of an area by land and forest type), standard simple random sampling formulas would define the number of photo points needed to estimate areas by land and forest type within given error limits. By these formulas (if photo interpretation were exact), approximately 500 photo points over the total private acreage would produce estimates of timberland area that would be correct plus or minus 3 percent 9 times out of 10. But photo interpretation is not exact; to ensure that proper percentages of land and forest type categories be established, a much larger photo sample was used. Interpretation of the photos covering the sections with private acreages produced land and forest type information for 5,453 photo points; or one photo point for every 278 acres.

Even though a ground sample was used to adjust percentages of land in different land and forest type categories, there is still a sampling error associated with area estimates. The sampling error for the estimate of timberland area for all owners derived from the 1971-75 inventory was 4.2 percent per million acres. As major categories such as timberland are broken down into more specific categories, this sampling error increases.

Total privately owned acreage, including 74,825 acres of Census (Bureau of the Census, U.S. Department of Commerce) and non-Census water, as extracted from the BLM lists, is 1,514,850 acres. Based on the photo interpretation and adjustments derived from the ground sample, 280,634 acres of timberland in the Tanana unit are privately owned. Other breakdowns of private land are: marginal timberland--36,172; inoperable forest land--766,809 acres; and nonforest land--356,409 acres. Additional detailed breakdowns of these results are provided in the tables 1 to 4.

Table 1—Area by land class and owner, Tanana inventory unit, interior Alaska, 1984[1]

	OWNER				
LAND CLASS	NATIVE ALASKAN	OTHER PRIVATE	TOTAL PRIVATE	PUBLIC	ALL OWNERS
			ACRES		
FOREST LAND:					
TIMBERLAND	235,117	45,517	280,634	1,914,045	2,194,680
MARGINAL TIMBERLAND	33,121	3,051	36,172	247,663	283,835
INOPERABLE FORESTLAND	716,068	50,741	766,809	8,079,341	8,846,150
TOTAL	984,306	99,309	1,083,615	10,241,049	11,324,664
NONFOREST LAND	316,723	39,686	356,409	1,414,659	1,771,068
ALL LANDS	1,301,029	138,995	1,440,024	11,655,708	13,095,732
CENSUS WATER	48,025	--	48,025	309,633	357,658
NON-CENSUS WATER	24,213	2,587	26,800	167,681	194,481
ALL CLASSES	1,373,268	141,582	1,514,850	12,133,021	13,647,872

[1]Totals may be off because of rounding.

Table 2—Area of timberland by survey block and owner, Tanana inventory unit, interior Alaska, 1984[1]

	OWNER				
SURVEY BLOCK	NATIVE ALASKAN	OTHER PRIVATE	TOTAL PRIVATE	PUBLIC	ALL OWNERS
			ACRES		
KANTISHNA	4,512	362	4,874	419,366	424,240
FAIRBANKS	42,343	28,957	71,300	676,677	747,977
WOOD SALCHA	40,806	15,493	56,299	569,972	626,271
UPPER TANANA	147,456	705	148,161	248,030	396,191
ALL BLOCKS	235,117	45,517	280,634	1,914,045	2,194,680

[1]Totals may be off because of rounding.

When the sampling and procedural errors are taken into account, the distribution of total, privately owned acreage into timberland and nontimberland categories is in error by no more than 15 percent. The total figure for privately owned land (1,514,850 acres) is not based on a sample, has no sampling error, and, given the 2-percent procedural error mentioned above, was true in March 1984.

Table 3—Area of timberland by owner, productivity class, and forest type, Tanana inventory unit, interior Alaska, 1984[1]

OWNER	CUBIC-FOOT PRODUCTIVITY CLASS	FOREST TYPE						
		BLACK SPRUCE	WHITE SPRUCE	BALSAM POPLAR	ASPEN	PAPER BIRCH	NON STOCKED	ALL TYPES
					ACRES			
NATIVE ALASKAN	85 AND MORE			--				
	50 to 85		-	-	--	--		
	LESS THAN 50	281	119,242	16,842	31,525	67,226	-	235,117
OTHER PRIVATE	85 AND MORE			-			--	--
	50 to 85	--	--	-	-			
	LESS THAN 50	89	7,996	1,728	13,417	22,287	-	45,517
TOTAL PRIVATE	85 AND MORE		-	--			--	--
	50 to 85			--	--	-	-	-
	LESS THAN 50	370	127,238	18,570	44,942	89,513		280,634
PUBLIC	85 AND MORE				--	-		--
	50 to 85	--	--	--	-	4,999	-	4,999
	LESS THAN 50	42,961	625,381	65,846	358,567	794,420	21,872	1,909,046
ALL OWNERS	85 AND MORE		-		-	--	--	--
	50 to 85	-	-	-	-	4,999	-	4,999
	LESS THAN 50	43,331	752,619	84,416	403,509	883,933	21,872	2,189,680
TOTAL		43,331	752,619	84,416	403,509	888,932	21,872	2,194,680

[1]Totals may be off because of rounding.

Table 4—Area of timberland by owner and stand-size class, Tanana inventory unit, interior Alaska, 1984[1]

OWNER	STAND-SIZE CLASS				
	SAWTIMBER	POLETIMBER	SEEDLING AND SAPLING	NON-STOCKED	ALL CLASSES
			ACRES		
NATIVE ALASKAN	75,085	87,949	70,108	1,975	235,117
OTHER PRIVATE	9,170	16,981	18,606	760	45,517
TOTAL PRIVATE	84,255	104,930	88,714	2,735	280,634
PUBLIC	431,953	757,557	705,396	19,137	1,914,045
ALL OWNERS	516,208	862,487	794,110	21,872	2,194,680

[1]Totals may be off because of rounding.

Terminology[1]

Census water—Streams, sloughs, estuaries, and canals more than one-eighth mile wide; and lakes, reservoirs, and ponds more than 40 acres in area. (Also see "Non-Census water.")

Forest land—Land at least 16.7 percent stocked by forest trees of any size or formerly having such tree cover, and not currently developed for nonforest use.

Forest types—A classification of forest land based on the species forming a plurality of the live tree stocking.

Black spruce[2] —Forests in which a plurality of the stand is black spruce. Black spruce most often occurs in nearly pure stands but can be found mixed with tamarack, white spruce, paper birch, and aspen. Black spruce is fairly characteristic of poorer forest land.

White spruce—Forests in which a plurality of the stand is white spruce. Common associates include paper birch and balsam poplar, and occasionally black spruce or quaking aspen.

Balsam poplar—Forests in which a plurality of the stand is balsam poplar. South of the Alaska Range balsam poplar may be replaced by black cottonwood or hybrids between the two. As the poplar ages it is sometimes replaced by white spruce; however, it is usually found as a nearly pure type with only an occasional white spruce or paper birch associate.

Paper birch—Forests in which a plurality of the stand is paper birch. Paper birch can occur in pure stands but is more often mixed with white spruce, quaking aspen, or black spruce.

Quaking aspen—Forests in which a plurality of the stand is aspen. Aspen is usually found as a pure type after fire and after a willow stage. As aspen ages it is usually replaced by spruce except on very dry sites where it may remain as a pure type. Common associates include black spruce and white spruce and occasionally paper birch.

Inoperable forest land—Nontimberland with a gross volume of less than 800 cubic feet per acre.

Land area—The area of dry land and land temporarily or partly covered by water such as marshes, swamps, and river flood plains (omitting tidal flats below mean high tide); streams, sloughs, estuaries, and canals less than 120 feet wide; and lakes, reservoirs, and ponds less than 1 acre in area.

Land class—A classification of land by major use, such as timberland, other forest, and nonforest. The minimum size area for classification is 1 acre.

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[1] Terminology is from the USDA Forest Service, Forest Service Handbook, Title 4813.1, 1967, and the manual of field instructions for the forest survey of the Tanana River Basin, Alaska, 1975.

[2] See "Names of Trees" for scientific names.

Marginal timberland—Nontimberland with a gross volume in excess of 800 cubic feet per acre.

Non-Census water—Streams, sloughs, estuaries, and canals between 120 feet and one-eighth mile wide; and lakes, reservoirs, and ponds between 1 and 40 acres in area. (Also see Census water.)

Nonforest land—Land that does not qualify as forest land. Includes land that has never supported forests and lands formerly forested where forest use is precluded by development for nonforest uses, such as crops, improved pasture, residential areas, and city parks. Also includes improved roads and certain areas of water classified by the Bureau of the Census as land. Unimproved roads, streams, canals, and nonforest strips in forest areas must be more than 120 feet wide, and clearings in forest areas must be more than 1 acre in size to qualify as nonforest land.

Nonstocked areas—Timberland less than 16.7 percent stocked with growing stock trees.

Nontimberland—Unproductive forest land incapable of yielding crops of industrial wood because of adverse site conditions (producing less then 20 cubic feet per acre per year) and productive forest land withdrawn from commercial timber use through statute or administrative regulation.

Other forest land—Unproductive forest land incapable of yielding crops of industrial wood because of adverse site conditions. This includes sterile or poorly drained forest land, subalpine forests, and steep rocky areas where topographic conditions are likely to prevent management for timber production indefinitely.

Poletimber stands—Stands at least 16.7 percent stocked with growing stock trees, of which half or more of this stocking is in poletimber and sawtimber trees, and with poletimber stocking exceeding that of sawtimber.

Productivity class—A classification of forest land in terms of potential growth in cubic feet of fully stocked natural stands.

Sawtimber stands—Stands at least 16.7 percent stocked with growing stock trees, with half or more of total stocking in sawtimber or poletimber trees, and with sawtimber stocking at least equal to poletimber stocking.

Seedling-sapling stands—Stands at least 16.7 percent stocked with growing stock trees, of which more than half of the stocking is saplings and seedlings.

Stand-size classes—A classification of forest land based on size of the growing stock present; that is, sawtimber, poletimber, or saplings and seedlings.

Timberland—Forest land producing or capable of producing crops of industrial wood and not withdrawn from timber utilization. Areas qualifying as timberland have the capability of producing in excess of 20 cubic feet per acre per year (mean annual increment) of industrial wood under management.

Names of Trees[3]

Common name	Scientific name
Softwoods:	
Black spruce	*Picea mariana* (Mill.) B.S.P.
Tamarack	*Larix laricina* (Du Roi) K. Koch
White spruce	*Picea glauca* (Moench) Voss
Hardwoods:	
Balsam poplar	*Populus balsamifera* L.
Paper birch	*Betula papyrifera*Marsh.
Quaking aspen	*Populus tremuloides*Michx.

[3/] Scientific names are according to Viereck and Little (1972).

Metric Equivalents

1 foot	=	0.3048 meter
1 mile	=	1.609 kilometers
1 acre	=	0.4047 hectare
1 cubic foot	=	0.0283 cubic meter

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*GPO 595 - 175 (1985)

van Hees, Willem W.S. Land ownership patterns in the Tanana River Basin, Alaska, 1984. Res. Pap. PNW-335. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 9 p.

Aerial photo sampling coupled with information taken on the ground provided data for development of estimates of land and forest area by ownership group within the boundaries of the 1971-75 Tanana River Basin timber inventory unit, Alaska. Area of privately owned timberland is estimated at 280,634 acres (113 569 hectares).

Keywords: Land owners, forest surveys, Alaska (Tanana River).

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Research Paper
PNW-336
May 1985

Calculating Moisture Content of 1000-Hour Timelag Fuels in Western Washington and Western Oregon

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Ottmar, Roger D.; Sandberg, David V. Calculating moisture content for 1000-hour timelag fuels in western Washington and western Oregon. Res. Pap. PNW-336 Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 16 p.

A predictive model is presented to calculate moisture content of 1000-hour timelag fuels in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) logging slash in western Washington and western Oregon. The model is a modification of the 1000-hour fuel moisture model of the National Fire-Danger Rating System and requires daily measurements of precipitation duration, maximum and minimum relative humidities, and maximum and minimum temperatures. Comparison of measured and calculated fuel moisture contents showed good agreement. The model allows managers to accurately calculate fuel moisture values from weather variables for fuel reduction estimates. Current fire-weather stations provide adequate weather data for satisfactory operation of the 1000-hour fuel moisture model.

Keywords: Fuel moisture content, fire danger rating.

mmary

A moisture model (ADJ-Th) has been developed that estimates within ±5 percent the average fuel moisture content for 1000-hour timelag fuels in western Washington and western Oregon logging slash. It is a modification of the 1000-hour fuel moisture model of the National Fire-Danger Rating System (NFDR-Th), adjusted to represent west-side fuel types. The model allows fire managers to accurately calculate moisture content of large, woody fuels from weather variables for fuel reduction estimates.

Direct measurement on a given day showed considerable variation in moisture content between logs. Statistics indicate that to assure an error of less than ±5 percent, a minimum of 20 fuel moisture samples must be collected. The NFDR-Th underpredicted average measured fuel moisture content for west-side logging units and overpredicted rate of change in the drying cycle. The error resulted from internal coefficients developed for ponderosa pine (*Pinus ponderosa* Dougl.) being tested against western redcedar (*Thuja plicata* Donn) as a "worst case" fire-danger rating. By calculating a ratio between the measured and predicted fuel moisture values that were preceded by 7 days of dry weather, then varying the environmental coefficient, we adjusted the NFDR-Th to provide the accuracy needed for predicting fuel reduction.

Current fire-weather stations provide adequate weather data for satisfactory operation of the 1000-hour fuel moisture model.

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roduction

Scheduling prescribed fire to achieve desired effects depends on the ability to predict large-fuel consumption. Sandberg and Ottmar (1983) developed an algorithm for predicting diameter reduction of large, woody fuels in broadcast-burned logging slash in the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) region of western Washington and western Oregon. The algorithm requires an average moisture content of 1000-hour timelag fuels.[1/]

The 1000-hour fuel moisture model of the National Fire-Danger Rating System (NFDR-Th) (Deeming and others 1977) was developed to calculate the moisture content of large, woody fuels. It has been tested successfully against a data set of measured fuel moisture values from western redcedar (*Thuja plicata* Donn) logs (Fosberg and others 1981). The model, however, cannot be applied accurately to the Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg) slash common to units[2/] in western Washington and western Oregon. Objectives of our study were to compare fuel-moisture calculations obtained from NFDR-Th with measured values, then to adjust the model to better represent those fuels.

This paper discusses the development and field evaluation of a regionally specific moisture model (ADJ-Th) (Ottmar 1980) that calculates a mean moisture content for woody material in the 3- to 9-inch-diameter size class of Douglas-fir and western hemlock logging slash in western Washington and western Oregon. The model, a modification of NFDR-Th, requires daily measurements of precipitation duration and maximum and minimum relative humidities and temperatures. A comparison test between fuel moisture contents calculated from offsite and onsite weather station data is also discussed.

view of NFDR-Th

In 1978, an updated version of the 1972 National Fire-Danger Rating System was released, amending deficiencies noted by scientists and users. One amendment was the addition of large fuels (1000-hour timelag class) that responded to long-term drying. A component of this system is the fuel moisture model for 1000-hour timelag fuels, developed by Fosberg (1972).

Fuel moisture is the cumulative effect of past and present weather events. Fosberg describes the change through a series of numerical and analytical solutions of the Fickian diffusion equation (Fosberg and others 1981). The basic equation for fuel moisture change is:

$$m = m_o + (m_b - m_o)\,(1 - \zeta \exp(-\delta t/\tau)); \quad (1)$$

where:

m = final fuel moisture,
m_o = initial fuel moisture,
m_b = 7-day average boundary condition,
ζ = environmental coefficient accounting for nonuniform moisture distribution inside the fuel and for environmental variations,
δt = time interval of actual moisture change, and
τ = timelag constant of the fuel.

[1/] Dead, woody fuels 3 to 9 inches in diameter.

[2/] As used in this report, unit refers to a timber-harvested site with unburned logging slash.

To make equation (1) appropriate for predicting moisture content of 1000-hour timelag fuels, Fosberg and others (1981) substituted the following:

δ = 0.82,
δt = 7 × 24 hours (averaging the boundary condition over 7 days), and
τ = 1000 hours.

Hence, equation (1) becomes:

$$m = m_o + (m_b - m_o)\,(1 - 0.82\,\exp(-168/1000))\,;$$

which is the basis for NFDR-Th.

Weather variables enter the model in the calculation of a daily boundary condition expressed as:

$$m_{bi} = \frac{(\delta t - P)\bar{m}_e + \delta_s\, c\, P_s + \delta_R\, P_R(aP_R + b)}{\delta_t}\,;$$

where:

m_{bi} = daily boundary condition,
δt = averaging time equal to 24 hours,
P_R = duration of precipitation (rain) in hours (0-24),
P_s = duration of precipitation (snow) in hours (0-24),
P = $P_R + P_s$, the total duration of precipitation in hours,
δ_s = Kronecker delta indicating occurrence of snow,
δ_R = Kronecker delta indicating occurrence of rain,
a = liquid uptake coefficient (2.7 percent/hr) (Fosberg 1972),
b = liquid uptake coefficient (76 percent) (Fosberg 1972), and
c = coefficient equal to 30, representing the mean fiber saturation point under snow.

$$\bar{m}_e = \frac{m_e(T_{max}, h_{min}) + m_e(T_{min}, h_{max})}{2}$$

where:

$\bar{m}_e$ = average equilibrium moisture content for wood. The equilibrium moisture content functions for temperature (°F) and relative humidity (%) (Simard 1968) are:

$$m_e = 0.03229 + 0.281073\,h - 0.000578h\,T,\ h \leq 10\%,$$

$$m_e = 2.22749 + 0.160107\,h - 0.014784\,T,\ 10\% < h \leq 50\%,\ \text{and}$$

$$m_e = 21.0606 + 0.005565\,h^2 - 0.00035h\,T - 0.483199\,h,\ h > 50\%;$$

T_{max} = maximum 24-hour temperature;
T_{min} = minimum 24-hour temperature;
h_{max} = maximum 24-hour humidity; and
h_{min} = minimum 24-hour humidity.

The 7-day average boundary condition is:

$$m_b = \frac{1}{7} \sum_{i=1}^{7} m_{bi} \quad . \qquad (5)$$

The NFDR-Th, defined by equations 1-5, was compared with the moisture content of western redcedar logs 6 inches in diameter and located on racks in clearcut units within Priest River Experimental Forest, northern Idaho (Brackebusch 1975). A correlation coefficient of 0.78 was reported (Fosberg and others 1981).

ethods

el Moisture Samples

In 1979, fuel moisture samples were collected and processed for evaluating and adjusting the NFDR-Th. Samples were collected from two 2.5-acre sample plots: one in an old-growth clearcut unit and one in a nearby shelterwood unit (20 stems/acre). Both units were in the Mount Baker-Snoqualmie National Forest in western Washington (figs. 1, 2, 3). Aspect (south-southwest), slope (less than 20 percent), and elevation (2,300 feet) were similar for both units. Woody fuels consisted of mixed Douglas-fir, western hemlock, and western redcedar.

Every 7 to 10 days between May and November, fuel moisture samples were collected. Twenty randomly chosen logs 3 to 9 inches in diameter were sampled from each plot. The logs were not sampled on days when water was present on their surface. A single cross section was removed from each log at least 2 feet from the end. The entire piece was sectioned, then sealed into a 1-pint, polypropylene, screw-cap bottle capable of withstanding an autoclave. Samples were weighed to an accuracy of 0.01 gram and placed into a laminar-flow hot-air oven set at 217 °F for a minimum of 48 hours. When removed from the oven, the samples were reweighed to determine a dry weight. Moisture loss was expressed as a percentage of dry weight.

eather Monitoring and FDR-Th Computation

An onsite weather station equipped with a hygrothermograph and rain gauge capable of weighing and recording provided daily maximum and minimum relative humidities and temperatures, and duration of precipitation for daily computation of NFDR-Th.

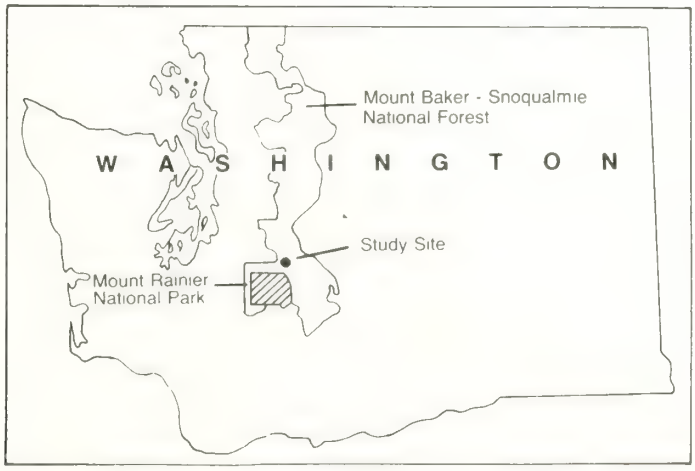

Figure 1.—Location of study sites.

Figure 2.—Partial-cut unit.

Figure 3.—Clearcut unit.

Results

Weather

Between May 1 and November 15, the weather consisted of extended dry perio intermixed with periods of precipitation (fig. 4), ideal for observing several dryin and wetting cycles of the dead, woody fuels.

Measured Fuel Moisture Contents

The mean moisture content (n = 20) of the 3- to 9-inch fuels decreased gradua from an initial high of 41 percent (fig. 4). Two minor increases occurred in Jun and one in early July because of several days of precipitation. Beginning July 1 a 32-day period of dry weather caused moisture contents to drop to 27 percent i the partial cut unit and 25 percent in the clearcut. During the rest of this sampl period, fuel moisture contents fluctuated up and down in response to periods c rain and dry weather.

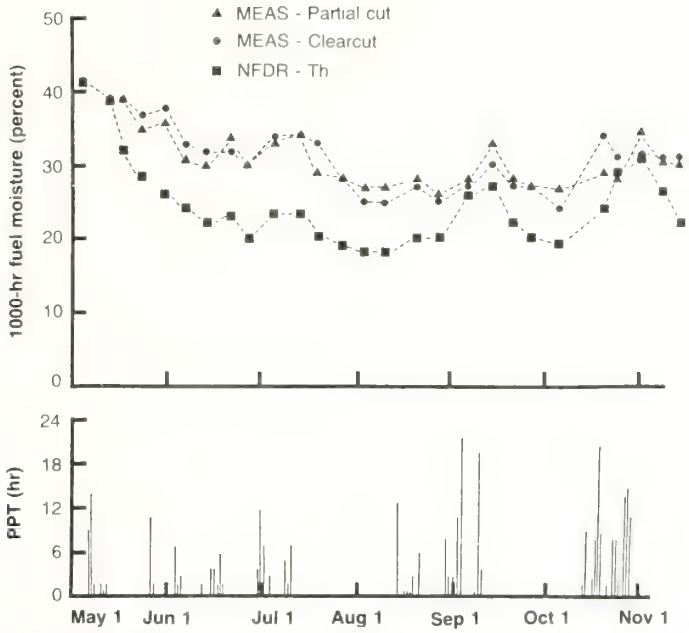

Figure 4.—Changes in fuel moistures, measured (MEAS) in partial cut and in clearcut units, fuel moistures calculated by NFDR-Th, and precipitation (PPT) duration. A moisture content initially measured at 41 percent was used as the starting value.

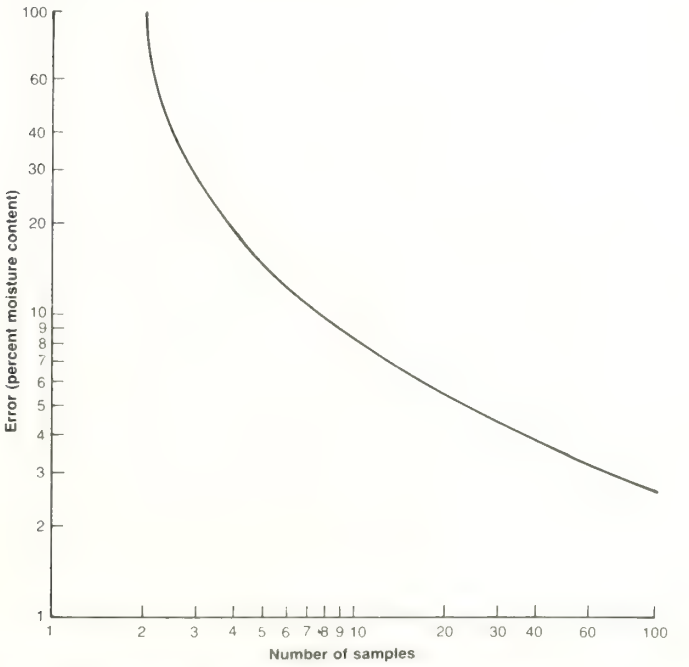

Figure 5.—Number of 1000-hour fuel moisture samples needed to achieve acceptable error.

On a given day, moisture content varied considerably between logs. Averaged over the 27 sampling periods, the standard deviation of moisture content was 12 percent in the clearcut unit and 11 percent in the partial cut unit. Because 20 samples were collected each week from each unit, the sample mean error was ±5 percent at the 95-percent confidence level (Freese 1974) (fig. 5). Sandberg and Ottmar's (1983) diameter reduction algorithm requires a fuel moisture error less than or equal to ±5 percent.

The fuel moisture contents measured during the sampling period averaged 31.1 percent in the partial cut unit (standard error of the mean 2.6 percent) and 31.2 percent in the clearcut unit (standard error of the mean 2.9 percent). The canopy cover of the partial cut unit appears to have had a minor influence on the fuel moisture content of large timelag fuels during this study.

NFDR-Th Calculations

Two differences were noted when comparing the measured fuel moisture values to the values calculated for the same fuels by NFDR-Th. First, the NFDR-Th model underpredicted moisture values by an average of 7 percent, ranging between 0 and −11 percent. Second, the NFDR-Th model overpredicted the rate of change in the drying cycles.

Measured fuel moistures were then separated by species and compared to the NFDR-Th values. The model underpredicted the Douglas-fir and western hemloc samples (fig. 6) but closely represented western redcedar logs (fig. 7). Fosberg and others (1981) developed the model's internal coefficients for ponderosa pine and tested the NFDR-Th against western redcedar. Western redcedar logs tend t have one of the lowest fuel moistures in a unit. This "worst-case" predictive approach is appropriate for the NFDR-Th model's intended purpose of rating fire danger; however, for planning prescribed fire, estimating fuel consumption, and anticipating fire effects, the forest manager requires a model that more accurately predicts an average unit fuel moisture content. NFDR-Th must be adjusted to account for Douglas-fir and western hemlock fuels, which compose a majority o the logging slash in western Washington and western Oregon.

Discussion

NFDR-Th Adjustment

The tendency of NFDR-Th to underpredict the average fuel moisture content of unit is related to several terms in the model, one of which is the equilibrium moisture content (m_e) as defined by the instantaneous temperature and humidity (USDA Forest Service 1974). Because the numbers are averages for all species of wood without bark, they may mask the true drying effect influenced by species and other natural physical characteristics (Fosberg 1971). An adjusted m_e improves the NFDR-Th for use in Douglas-fir and western hemlock logging slash common to western Washington and western Oregon.

We rearranged terms in the basic 1000-hour fuel moisture model (eq. 2) to solve for the 7-day average boundary condition (m_b). Because m_b is defined in terms of the equilibrium moisture content during a 7-day rainless period, the boundary condition equation becomes a formula for equilibrium moisture content:

$$m_b = \bar{m}_{e7} = 3.26(m - m_o) + m_o.$$

Consequently, an adjustment factor can be calculated through analysis of measured and calculated fuel moisture contents that are preceded by dry weather.

Seven days of dry weather preceded 13 of the 27 sampling periods during our study. This enabled average equilibrium moisture content ($\bar{m}_{e7}$) to be calculated for 13 measured and NFDR-Th fuel moisture contents (table 1). By totaling the values for the measured moisture content and those for the calculated moisture content, we formulated a ratio. The resultant adjustment factor, using the environmental coefficient (ζ) = 0.82, was 325/203 or 1.60 times the value of equilibrium moisture content computed from the NFDR-Th predictive model.

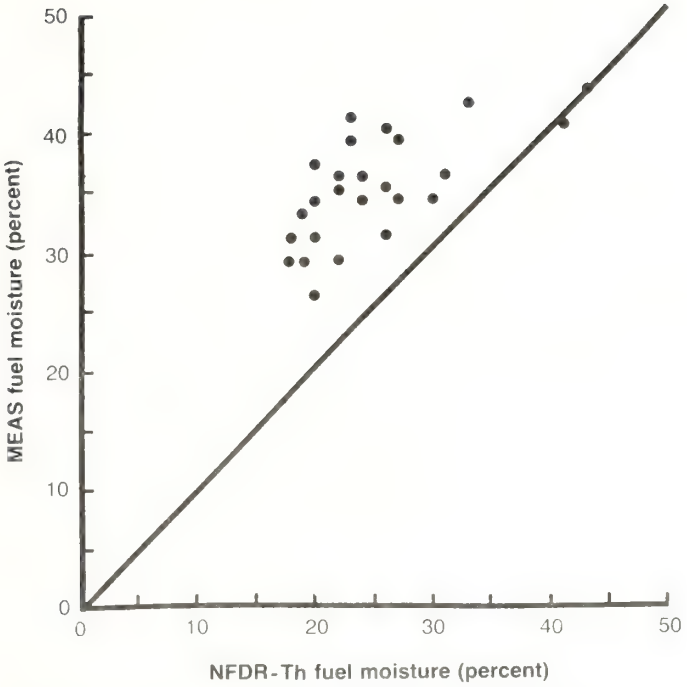

Figure 6.—Moisture values measured (MEAS) in samples of Douglas-fir and western hemlock versus values calculated by NFDR-Th. A moisture content initially measured at 43 percent was used as the starting value for NFDR-Th. The solid line indicates a perfect fit.

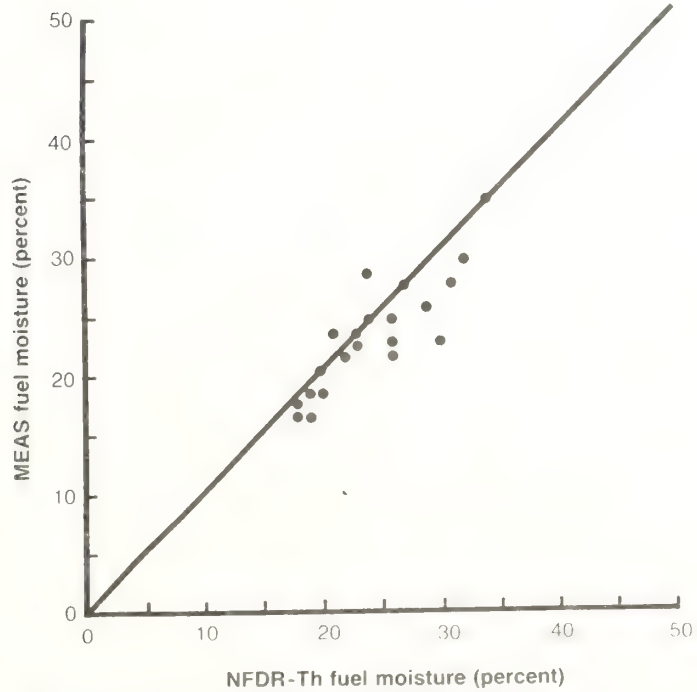

Figure 7.—Moisture values measured (MEAS) in samples of western redcedar versus values calculated by NFDR-Th. A moisture content initially measured at 34 percent was used as the starting value for NFDR-Th. The solid line indicates a perfect fit.

Table 1—Initial (m_o) and final (m) fuel moistures, and average equilibrium moisture content ($\bar{m}_{e7}$) computed from moisture contents measured and those calculated by NFDR-Th for 1000-hour timelag fuels during 13 sampling periods preceded by 7 days of dry weather

(In percent)

Date, 1979	Moisture content			Moisture content calculated by NFDR-Th		
	m_o	m	m_{e7}	m_o	m	m_{e7}
05-16	39	39	39	39	32	16
05-22	39	36	29	32	29	22
06-14	32	31	29	29	27	18
06-27	32	30	25	26	24	15
07-19	33	31	24	25	23	14
07-26	31	28	21	23	22	17
08-02	28	26	21	22	21	16
08-09	26	25	23	21	20	15
08-27	27	25	20	21	21	21
09-21	32	27	16	25	23	14
10-03	27	26	24	21	19	10
11-09	33	31	26	28	25	11
11-15	31	30	28	25	23	14
Total			325			203

Because the environmental coefficient (ζ) may vary with species and environmental condition, an optimal combination of ζ and an adjustment factor for equilibrium moisture content will exist. To test for this optimal combination, we varied ζ from 0.5 to 1.0, with an adjustment factor for equilibrium moisture conten calculated for each value tested. An environmental coefficient of 0.97 and an adjustment factor of 1.4 were shown by the hypothesized variance test (Freese 1960) to best calculate the measured values (± 3 percent at the 95-percent confidence interval, fig. 8). A final comparison of NFDR-Th and ADJ-Th is:

NFDR-Th:

$$m = m_o + (m_b - m_o)(1 - 0.82 \exp(-168/1000)) ;$$

ADJ-Th:

$$m = m_o + (m_b - m_o)(1 - 0.97 \exp(-168/1000)) ;$$

where the daily equilibrium moisture content (eq. 4) is adjusted by a factor of 1.4

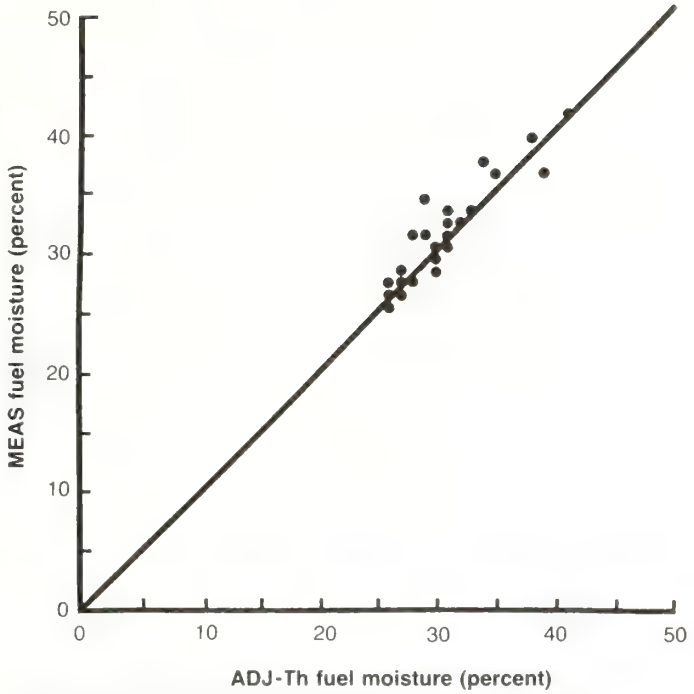

Figure 8.—Moisture values measured (MEAS) versus those calculated by ADJ-Th. The solid line indicates a perfect fit.

-Th Evaluation

Measured fuel moisture contents from seven partial-cut units and eight clearcut units located in western Washington and western Oregon were used to test the ADJ-Th. Weather data used to calculate ADJ-Th was obtained from onsite fire-weather stations. The seasonal starting value was assumed to be 40 percent, a reasonable late-spring figure based on fuel moisture sampling in 1979, 1980, and 1981. The ADJ-Th algorithm predicted the average unit fuel moisture content within ±4 percent at the 95-percent confidence level, with a range between −4 and +5 percent (fig. 9). The NFDR-Th underpredicted these average unit moisture contents by an average of 11 percent, with a range between −5 and −20 percent (table 2). The ADJ-Th has not been tested on sites with long-needled slash.

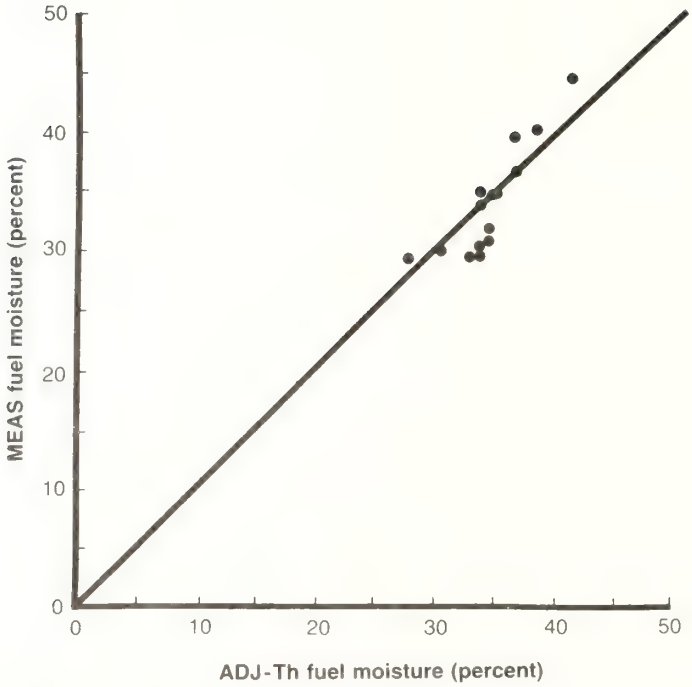

Figure 9.—Moisture values measured (MEAS) in 15 units logged in western Washington and western Oregon and values calculated by ADJ-Th. Weather data were collected from onsite weather stations. The solid line indicates a perfect fit.

Table 2—Fuel moisture contents measured (MEAS), calculated by NFDR-Th, and calculated by ADJ-Th for 1000-hour timelag fuels in 7 partial-cut and 8 clearcut units in western Washington and western Oregon

Name of unit	National Forest	Date of sampling	Number of samples	Moisture content[1]				
				MEAS	NFDR-Th[2]	Difference from MEAS	ADJ-Th[2]	Difference from MEAS
				Percent				
Partial cut:								
Quentin	Willamette	06-08-78	4	39	30	- 9	37	-2
Bow Sky	Mount Hood	06-08-78	4	44	24	-20	40	-4
Suntop I	Mount Baker-Snoqualmie	06-20-78	4	40	28	-12	37	-3
Andy I	Mount Baker-Snoqualmie	06-28-78	4	37	24	-13	37	0
Timber Butte	Willamette	06-28-78	4	35	23	-12	34	-1
Suntop II	Mount Baker-Snoqualmie	07-12-78	5	33	23	-10	33	0
Pamelia II	Willamette	07-30-78	8	29	17	-12	28	-1
Clearcut:								
Green Mountain-2	Willamette	07-13-81	35	32	23	- 9	35	+3
Green Mountain-3	Willamette	07-14-81	33	30	23	- 7	34	+4
Joule	Willamette	07-23-82	32	29	24	- 5	33	+4
Blackeye 2	Mount Hood	05-26-83	33	29	24	- 5	34	+5
Blackeye 20	Mount Hood	05-26-83	29	34	24	-10	34	0
Blackeye 3	Mount Hood	05-26-83	39	31	24	- 7	34	+3
Blackeye 30	Mount Hood	05-26-83	36	34	24	-10	34	0
Blackeye 1	Mount Hood	06-08-83	35	30	22	- 8	31	+1

[1] Seasonal starting value was assumed to be 40 percent.

[2] Weather data used to calculate NFDR-Th and ADJ-Th were obtained from onsite weather stations.

ite Weather Stations

Measured fuel moisture contents from 9 partial cut units and 21 clearcut units in western Washington and western Oregon were compared with ADJ-Th fuel moisture contents calculated from data recorded by offsite weather stations. These existing fire-weather stations were identified by local managers as being most likely to represent onsite conditions. When we used the hypothesized variance test (Freese 1960), ADJ-Th predicted fuel moisture contents within the ±5 percent error acceptable for estimating fuel reduction (table 3, fig. 10). This evidence suggests that current fire-weather stations provide adequate data for operation of the 1000-hour fuel moisture model.

Table 3—Fuel moisture contents measured (MEAS) and calculated by ADJ-Th for 1000-hour timelag fuels in 9 partial cut and 21 clearcut units in western Washington and western Oregon

Name of unit	National Forest	Date of sampling	Number of samples	Moisture content[1] MEAS	Moisture content[1] ADJ-Th[2]	Difference from MEAS
				Percent		
Partial cut:						
Humpy I	Rogue	08-31-77	2	15	19	+4
Humpy II	Rogue	09-17-77	2	16	19	+3
Quentin	Willamette	06-08-78	4	39	35	-4
Bow Sky	Mount Hood	06-08-78	4	34	32	-2
Suntop I	Mount Baker-Snoqualmie	06-20-78	4	40	37	-3
Andy I	Mount Baker-Snoqualmie	06-28-78	4	37	37	0
Timber Butte	Willamette	06-28-78	4	35	34	-1
Suntop II	Mount Baker-Snoqualmie	07-12-78	5	33	34	+1
Pamelia II	Willamette	07-30-78	8	29	28	-1
Clearcut:						
Lower Till	Mount Hood	06-30-80	14	33	36	+3
Upper Till	Mount Hood	06-30-80	14	33	36	+3
Sedge	Mount Hood	07-01-80	11	40	42	+2
N-84	Olympic	08-23-80	8	25	27	+2
Cobble	Mount Hood	08-28-80	22	31	29	-2
C-150	Olympic	09-10-80	13	26	29	+3
Collawash	Mount Hood	09-17-80	10	24	25	+1
Agate	Mount Hood	06-28-81	21	37	36	-1
Green Mt. 2	Willamette	07-13-81	35	32	35	+3
Green Mt. 3	Willamette	07-14-81	33	30	34	+4
Ericson A	Siuslaw	08-06-81	37	30	33	+3
Ericson C	Siuslaw	08-06-81	34	38	33	-5
French Creek[3]	Umpqua	10-28-81	39	26	26	0
North Slope #7[3]	Rogue	07-13-83	23	34	30	-4
North Slope #8[3]	Rogue	07-14-83	19	37	30	-7
North Slope #6[3]	Rogue	07-15-83	24	33	30	-3
Cataract[3]	Siuslaw	08-18-83	12	29	36	+7
Maria[3]	Siuslaw	08-21-83	17	31	36	+5
Cataract Hold[3]	Siuslaw	09-17-83	15	32	36	+4
Maria Hold[3]	Siuslaw	09-21-83	16	37	36	-1
Yoncalla[3]	Siuslaw	09-23-83	14	32	33	+1

[1] Seasonal starting value was assumed to be 40 percent.

[2] Weather data used to calculate ADJ-Th were obtained from offsite weather stations representing onsite conditions.

[3] Data used to calculate ADJ-Th were obtained from Remote Automatic Weather Station (RAWS).

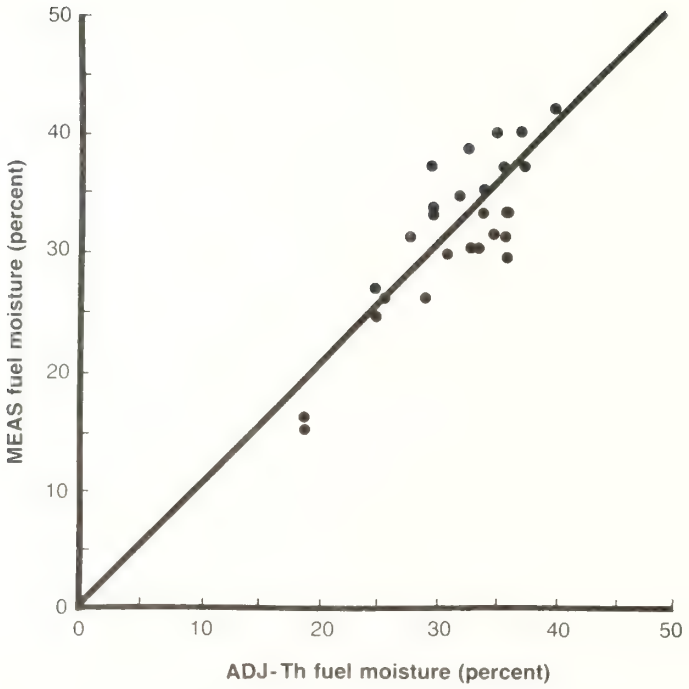

Figure 10.—Moisture values measured (MEAS) from 30 units logged in western Washington and western Oregon and values calculated by ADJ-Th. Weather data were collected from the offsite weather stations representing onsite conditions. The solid line indicates a perfect fit.

Application

The ADJ-Th moisture model replaces the need for direct fuel moisture measurements to determine an average unit fuel moisture. The model allows fire managers to accurately calculate an average unit fuel moisture content from weather variables for estimating fuel reduction. By assuming daily maximum and minimum relative humidities and temperatures and no precipitation, the forest manager can project fuel moisture and thereby determine the earliest date when burning can be prescribed for a unit.[3/]

Manually Calculating the ADJ-Th

A nomogram for manually calculating the ADJ-Th has been produced by Bob Burgan of the USDA Forest Service, Intermountain Forest and Range Experimen Station (appendix). The format and operation are identical to the 1000-hour fuel moisture nomogram presented by Burgan and others (1977). This nomogram wil enable forest managers to calculate a representative 1000-hour fuel moisture cor tent for logging slash in western Washington and western Oregon by using two weather variables: 24-hour average relative humidity and 24-hour precipitation duration. The system has been simplified to facilitate manual calculations. Hence the manually calculated values will not match perfectly with those produced by the computer model, but the error is minimal (Burgan and others 1977).

[3/] Peterson, Janice L. Using NFDRS-predicted 1000-hour as a daily management tool. Manuscript in preparation.

cknowledgment

Special thanks to Al Giudetti and Rod Hoibakk of the White River Ranger District, Mount Baker-Snoqualmie National Forest, Seattle, Washington, for their support and assistance in establishing the fuel moisture test sites. We are also indebted to personnel of the 17 Ranger Districts in 8 National Forests and the Pacific Northwest Region, USDA Forest Service, who cooperated and assisted in providing weather data and sites for testing the ADJ-Th.

tric Equivalents

1 inch = 2.54 centimeters
1 foot = 30.48 centimeters, or 0.3048 meter
1 acre = 0.4047 hectare
1 pint = 0.5506 liter (liquid)
1 gram = 0.0353 ounce
°F = 1.8 (°C) +32

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Appendix

Using the ADJ-Th Nomograms[1/]

1. Determine the average relative humidity and number of hours precipitation fell during a 24-hour period.

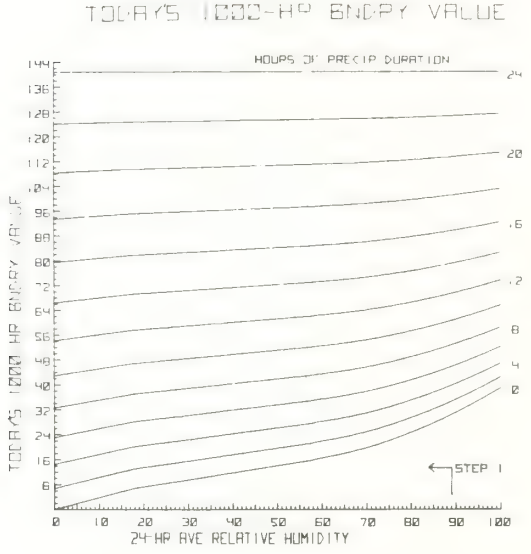
2. Using Nomogram 1, enter the 24-HR AVE RELATIVE HUMIDITY on the X-axis and draw a vertical line to the appropriate curve for precipitation duration. Draw a horizontal line left across the nomogram from that point to determine TODAY'S 1000-HR BNDRY VALUE.

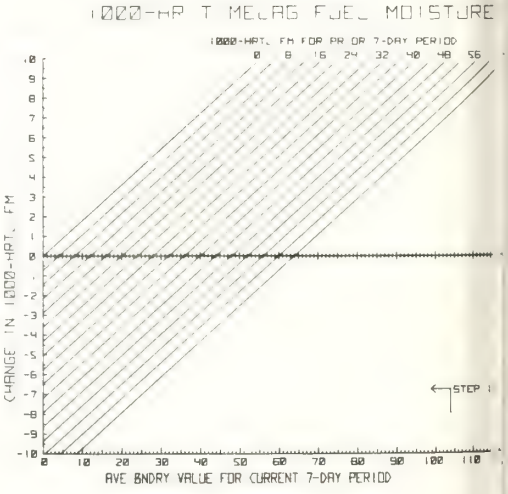
3. Determine TODAY'S 1000-HR BNDRY VALUE for 7 days and calculate an average.

4. Using nomograph 2, enter the AVE BNDRY VALUE FOR CURRENT 7-DAY PERIOD on the X-axis and draw a vertical line to the appropriate 1000-HRTL FM FOR PRIOR 7-DAY PERIOD. Draw a horizontal line left across the nomogram from that point to determine the CHANGE IN 1000-HRTL FM.

5. Add the CHANGE IN 1000-HRTL FM to the 1000-HRTL FM FOR PRIOR 7-DAY PERIOD to determine the current value.

6. The nomogram starting value can be determined from fuel moisture samples collected in the field or by using an approximate spring season value of 40 percent.




1000-HRTL FM FOR PR OR 7-DAY PERIOD
0 8 16 24 32 40 48 56
CHANGE IN 1000-HRTL FM
STEP 1
0 10 20 30 40 50 60 70 80 90 100 110
AVE BNDRY VALUE FOR CURRENT 7-DAY PERIOD

[1/] Refer to Burgan and others (1977) for more detailed instructions.

*GPO 595 - 797 (1985

Ottmar, Roger D.; Sandberg, David V. Calculating moisture content for 1000-hour timelag fuels in western Washington and western Oregon. Res. Pap. PNW-336. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 16 p.

A predictive model is presented to calculate moisture content of 1000-hour timelag fuels in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg) logging slash in western Washington and western Oregon. The model is a modification of the 1000-hour fuel moisture model of the National Fire-Danger Rating System and requires daily measurements of precipitation duration, maximum and minimum relative humidities, and maximum and minimum temperatures. Comparison of measured and calculated fuel moisture contents showed good agreement. The model allows managers to accurately calculate fuel moisture values from weather variables for fuel reduction estimates. Current fire-weather stations provide adequate weather data for satisfactory operation of the 1000-hour fuel moisture model.

Keywords: Fuel moisture content, fire danger rating.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

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Research Paper
PNW-337
May 1985

Comparison of Logging Residue from Lump Sum and Log Scale Timber Sales

James O. Howard and Donald J. DeMars

PUBLIC DOCUMENTS

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Abstract

Howard, James O.; DeMars, Donald J. Comparison of logging residue from lump sum and log scale timber sales. Res. Pap. PNW-337. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 8 p.

Data from 1973 and 1980 logging residues studies were used to compare the volume of residue from lump sum and log scale timber sales. Covariance analysis was used to adjust the mean volume for each data set for potential variation resulting from differences in stand conditions. Mean residue volumes from the two sale types were significantly different at the 5-percent level for the 1973 data but were not significantly different for the 1980 data. These inconclusive findings suggest that the relative efficiency of changing sales procedures should be considered before further study is undertaken.

Keywords: Residues, timber sales, wood utilization.

Summary

Regional timber supplies can be enhanced by increasing utilization from current timber harvest. One way to increase utilization from Federal lands may be to modify timber sale procedures, an option being examined by the USDA Forest Service. Of particular interest is whether lump sum timber sales result in greater utilization than log scale sales. The objective of our study was to determine if a significant difference in timber utilization exists between lump sum and log scale sales in western Oregon.

For the study, logging residue volume was used as an indication of utilization. Data used for the analysis came from two studies conducted in 1973 and 1980 on timberland in western Oregon managed by the USDA Forest Service and the U.S. Department of the Interior, Bureau of Land Management. Differences in residue volume between the two sale methods were tested by multiple covariance analysis; a separate analysis was made for data from each study. Because the data came from different agencies, mean residue volume was adjusted by covariance to account for potential variation attributable to differences in stand conditions.

Analysis of the data consisted of two phases. In the first phase, data on log scale sales were pooled with data from lump sum sales for both the 1973 and 1980 studies. A model was then developed from the stepwise regression fit of the pooled data. The second phase of analysis used covariance techniques to test for significant differences in logging residue volume between the two sale types.

Variance and regression coefficients for the two sale types were not significantly different for either the 1973 or the 1980 data. Results of an F-test indicated that adjusted means of the two sale types were significantly different at the 5-percent level for the 1973 data but were not significantly different for the 1980 data.

The inconclusive nature of these results suggests need for further study. A first step, however, would be to consider the relative efficiency of changing sale procedures, given the small difference shown in this study. An additional consideration is that any difference in utilization between sale types will decrease in the future because of changing technology and resource conditions.

Introduction

A study was conducted to test the common assumption that lump sum and log scale procedures result in different rates of timber utilization. Impetus for the study came from two situations: (1) a general tightening of timber supplies has caused land owners to look for ways to increase the amount of wood available for harvest; and (2) a challenge has directed the USDA Forest Service in the Intermountain, Pacific Southwest, and Pacific Northwest Regions to find ways to increase timber supplies through more effective utilization. The study addresses the latter; specifically, how to increase utilization from existing harvests.

Options available to enhance timber supplies have either long-term or short-term effects. Taking advantage of silvicultural or genetic opportunities will speed up individual tree growth or will increase productivity on existing stands, but gains will be in the future rather than now. An exception providing some flexibility results from the allowable cut effect, an accounting procedure that allows increased harvests today attributable to anticipated future yields from current silvicultural prescriptions. Less flexible are management activities directed at short-term gains. On Federal lands, where timber supplies are regulated by the allowable cut, an option for increasing short-term production is greater utilization from existing timber harvest.

Increases in utilization can result from technological changes in harvesting, marketing, or milling of the timber. The Forest Service is examining timber marketing procedures. In western Oregon, where data for this study were collected, the Forest Service uses log scale sales to market timber. Under this procedure logs removed from a sale are scaled and assessed a value using the average stumpage bid made by the purchaser. Occasionally small logs or cull logs are sold on a per-acre basis and are paid for in lump sum. Such PAM (per-acre material) sales account for only a small portion of the total Forest Service harvest.

Lump sum sales are one alternative to log scale sales. Timber in a lump sum sale is assessed and given a specific value; it is then sold on a lump-sum basis. Thus, scaling the logs removed by the purchaser is not required to establish payment. A commonly held assumption is that the purchaser will remove more material from the sale because a payment is not required for each log taken. A good description of each type of log scale is contained in a report by Brown and others (1982).

The apparent incentive of lump sum selling is centered on smaller or lower quality (marginal) logs. In a log scale sale, a marginal log of equal size and net volume will cost the purchaser the same as a log of higher quality. This situation does not exist in lump sum sales. Hence, the purchaser may be likely to remove marginal logs on lump sum sales, thereby increasing utilization from the sale. At issue, then, is whether the difference in utilization between the two types of sales is real or theoretical. A major question to be answered by the Forest Service is whether utilization would increase from use of lump sum sales procedures. An accompanying issue is whether a change from current sales practices would be cost effective. The latter issue, however, is not within the scope of this paper.

Methods

Data Source

For our study, volume of residual wood on the ground following harvest was used as an indicator of utilization. There were several reasons: (1) Readily accessible data on actual utilization levels[1/] for many sales were not available. (2) Volume measurement techniques for log scaling are somewhat different from techniques used to cruise standing trees. Comparing volumes obtained by both techniques could lead to inconsistent results. (3) The availability of a substantial block of logging residue data, including information on stand characteristics, provided a reasonable approach for the study.

Data used came from two studies conducted in western Oregon in 1973 (Howard 1978) and 1980 (Howard 1981). Ideally the data would have included information for both types of sales from a single agency, but this was not possible. Lump sum sales are not widely used by the Forest Service in western Oregon, and the Bureau of Land Management (BLM), and the U.S. Department of the Interior, does not use log scale procedures. It was therefore necessary to use data from BLM for lump sum sales and data from the Forest Service for log scale sales.

Although data from the two studies were similar, they were not compatible because size standards used to determine logging residue volume were different. For the 1973 study, the minimum size standard was 3.5 inches in diameter inside the bark and at least 4 feet in length. For the 1980 study, the dimensions were 3 inches in diameter and 1 foot in length. Because of the differences, the data were analyzed separately.

The sampling design used to estimate volume of logging residue was the line intersect method (Howard and Ward 1972). For the 1973 and 1980 studies, there were thirty or forty 200-foot transects on a systematic grid on each clearcut. Any logging residue material larger than the minimum size and intersected by a transect line was measured and used to compute the volume of logging residue. Other variables for which estimates were recorded were volume of the stand before cutting, stand defect (1973 data only), size of the cutting unit, stand age, average diameter of the stand, and percent slope.

Analysis

Multiple covariance analysis was used to test for differences in residue volume between the two sale methods; a separate analysis was made for data from the 1973 and 1980 studies. Because the data came from two agencies, mean residue volume was adjusted by covariance to account for potential variation attributable to differences in stand conditions.

[1/] Level of utilization for a specific sale is represented by the volume of timber removed divided by the initial volume offered for sale.

Analysis of the data consisted of two phases. In the first phase, data on log scale sales were pooled with data from lump sum sales for both the 1973 and the 1980 studies. We then developed a model from the stepwise regression fit of the pooled data. The model, based on previous work by Howard (1978), has two forms:

$$Y_{73} = b_{10} + b_{11}x_1^{0.5} + b_{12}x_2^2 + b_{13}x_2^{0.5} + b_{14}x_3^{-1} + b_{15}x_4^{-1} + b_{16}x_4^2, \text{ and}$$

$$Y_{80} = b_{20} + b_{21}x_1^{0.5} + b_{22}x_1^2 + b_{23}x_3^{-1} + b_{24}x_4^{-1} + b_{25}x_4^2;$$

where:

Y_{73}	=	volume of logging residue for 1973, in cubic feet per acre;
Y_{80}	=	volume of logging residue for 1980, in cubic feet per acre;
X_1	=	board foot volume of timber harvested per acre;
X_2	=	average percent of defect in harvested stand;
X_3	=	size of cutting, unit in acres;
X_4	=	stand age of at time of harvest;
$b_{10}, b_{11}, \ldots b_{16}$	=	regression coefficients for 1973 data; and
$b_{20}, b_{21}, \ldots b_{25}$	=	regression coefficients for 1980 data.

The second phase of the analysis used covariance techniques to test for significant differences in logging residue volume between lump sum and log scale sales. The first covariance technique was to test for homogeneity of variance between data sets. If variances were homogeneous, then we determined differences in the shape of the curve forms by testing for significant differences of regression coefficients, either singly or in common. The final covariance technique was to test for different intercepts or adjusted means, a test that was valid only if the data sets were homogeneous and equations described the same curve form.

Results of Analysis

Tables 1 and 2 give statistics for the pertinent covariance analysis of the 1973 and 1980 data. The test for homogeneity of variance for the data sets used a two tailed F test: the larger mean square error for a given year was divided by the smaller and the resulting F value was compared to a tabular value (Snedicor and Cochran 1967) at the 2.5-percent level to obtain a 5-percent test. For the 1973 data, the calculated F value was 1.04, with 72 and 73 degrees of freedom. Because the P value was greater than 0.5 in the two-tailed test, we accepted the hypothesis that the variances were the same. For the 1980 data, the calculated F value was 1.80, with 14 and 10 degrees of freedom, giving P a value of about 0.4 in the two-tailed test. Again, we accepted the hypothesis that the variances were the same.

The test for differences in regression coefficients of the two data sets also employs an F test. For the 1973 data, the F value was 0.83, with 6 and 145 degrees of freedom (table 1). This supports the null hypothesis that there is no difference in the regression coefficients. The test for differences in regression coefficients was not needed for the 1980 data because neither of the individual regressions were significant.

Table 1—Analysis of covariance for data on logging residue from 1973 timber sales in western Oregon

Source	Total		From regression			Error of estimate			
	Degree of freedom	Sum of squares	Degree of freedom	Sum of squares	Mean square	Degree of freedom	Sum of squares	Mean squares	F
Log scale sales	78	242582670	6	75293296	12548883	72	167289373	2323464	5.40 *
Lump sum sales	79	229461162	6	66331909	11055318	73	163129252	2234647	4.95 *
Within						145	330418626	2278749	
Regression coefficient						6	11342355	1890393	0.83 NS
Common	157	472043831	6	130282850	21713808	151	341760981	2263318	
Adjusted means						1	13424090	13424090	5.93 *
Total	158	495496098	6	140311027	23385171	152	355185072	2336744	

* = significant at P $\leq$ 5 percent .
NS = nonsignificant.

Table 2—Analysis of covariance for data on logging residue from 1980 timber sales in western Oregon

Source	Total		From regression			Error of estimate			
	Degree of freedom	Sum of squares	Degree of freedom	Sum of squares	Mean square	Degree of freedom	Sum of squares	Mean squares	F
Log scale sales	19	47682059	5	13591440	2718288	14	34090618	2435044	1.12 NS
Lump sum sales	15	22000778	5	8438878	1687776	10	13561900	1356190	1.24 NS
Within						24	47652519	1985522	
Regression coefficient						5	10627345	2125469	1.07 NS
Common	34	69682337	5	11402974	2280595	29	58279864	2009650	
Adjusted means						1	227392	227392	0.11 NS
Total	35	71591736	5	13084431	2616896	30	58507256	1950242	

NS = nonsignificant.

Table 3—Unadjusted means, adjusted means, and standard error of adjusted means of logging residue volume from timber sales in western Oregon

(In cubic feet per acre)

Source	Unadjusted means	Adjusted means	Standard error adjusted means
1973 data:			
Log scale sales (Forest Service)	4,387.08	4,322.71	178.12
Lump sum sales (BLM)	3,618.95	3,682.51	176.90
1980 data:			
Log scale sales (Forest Service)	3,580.60	3,467.52	363.41
Lump sum sales (BLM)	3,117.19	3,258.54	418.27

Table 3 gives the unadjusted and adjusted means for logging residue volume. The test for significant differences in the adjusted means of the 1973 data is given in table 1; the F value was 5.93, based on 1 and 151 degrees of freedom. Comparing this value with tabular values shows that the adjusted means are significantly different at the 5-percent level, but are not significantly different at the 1-percent level The test for significant differences in the adjusted means of the 1980 data (table 2) shows an F value of 0.11, with 1 and 29 degrees of freedom. This test favors the null hypothesis that the adjusted means for the 1980 data are not significantly different.

Discussion

Results of the analysis are inclusive in determining whether there was less logging residue from lump sum sales than from log scale sales. Although mean residue volume was larger for log scale than for lump sum sales (table 3), statistical tests show conflicting results: at the 5-percent level adjusted means are significantly different for the 1973 data but are not significantly different for the 1980 data.

There were reasons for keeping the 1980 data despite the small sample size. First, there was no statistical basis for eliminating the data. The sample seems to be representative with no detectable abnormalities that suggest elimination. Analysis of the values in table 3 show that the large differences between standard error of the mean for 1973 and 1980 is due, in part, to the differences in sample size. Another reason for not discarding the 1980 data is that the results for the 2 years, although different, may be correct. Changes in administrative procedures of timber sales or changes in timber utilization between 1973 and 1980 could account for the apparently conflicting results. The amount of logging residue can be affected greatly by such changes.

It would be somewhat difficult, and beyond the scope of this study, to determine the extent of administrative changes between 1973 and 1980. More can be said, however, about timber utilization. There has been a general trend toward better utilization for many years, brought about by changing yarding standards, greater product diversity, and more efficient harvest technology. Other factors may also have played a role in reducing residue levels. The expected result would be a greater reduction of residue materials where initial volumes were larger. In our study residue volumes in 1973 were greater on Forest Service lands than on BLM lands, and, subsequently incurred the largest decrease by 1980. Table 3 shows that volume of residue on Forest Service lands dropped 806 cubic feet per acre between 1973 and 1980, whereas the decrease on BLM lands was 502 cubic feet. The importance of this reduction is not so much what has occurred, but what will happen in the future. Because of the factors mentioned above and a movement toward harvesting second growth timber, residue levels will continue to decline. As residue volumes decreased, so will the difference between sale types. Also changing will be the characteristics of residue materials. In the future, residue will comprise fewer larger pieces, leaving mostly rotten logs, branches, and tops. But the rotten logs, branches, and tops will most likely be left as residue regardless of which sale procedure is used. Based on all these conditions it is likely that sale type will have a declining impact on residue volume. If this is the case, the issue of sale procedures affecting utilization should be looked at in terms of economic efficiency. A valid question might be: what are the costs of changing timber sale procedures in light of declining differences in residue volumes?

The results of this study are inconclusive and do not demonstrate significant differences in residue volume between lump sum and log scale sales. Two options seem evident from this conclusion. (1) evaluate the relative efficiency of changing from lump sum to log scale sales, based on the magnitude of differences in residue volume displayed in this study; and (2) conduct another study to verify whether the 1980 data is, in fact, representative of the current impact these two sale types have on residue levels. Ideally such a study would be conducted on sales administered by one agency. This is nearly impossible, however, because neither the Forest Service nor BLM use both sale types to any extent within the same geographic area. Therefore we recommended that additional study, if deemed appropriate, follow the design used in this study, using data from numerous sales of each type.

One point to be considered in interpreting the results of this study is the way in which the agencies conduct timber sales. Use of these results in evaluating the impact the two sales have on utilization would be adversely affected if either agency had an inherent advantage in applying one of the sales procedures. We conclude that both agencies would effectively administer either of the sales procedures.

Metric Equivalents

1 inch	=	2.54 centimeters
1 foot	=	30.48 centimeters
1 cubic foot	=	0.028317 cubic meter
1 acre	=	0.4047 hectare

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Howard, James O.; DeMars, Donald J. Comparison of logging residue from lump sum and log scale timber sales. Res. Pap. PNW-337. Portland, OR: U.S. Department of Agriculture. Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 8 p.

Data from 1973 and 1980 logging residues studies were used to compare the volume of residue from lump sum and log scale timber sales. Covariance analysis was used to adjust the mean volume for each data set for potential variation resulting from differences in stand conditions. Mean residue volumes from the two sale types were significantly different at the 5-percent level for the 1973 data but were not significantly different for the 1980 data. These inconclusive findings suggest that the relative efficiency of changing sales procedures should be considered before further study is undertaken.

Keywords: Residues, timber sales, wood utilization.

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Research Paper
PNW-341
July 1985

Height Growth and Site Index Curves for Douglas-Fir on Dry Sites in the Willamette National Forest

Joseph E. Means and Mary E. Helm

CLEMSON UNIVERSITY
OCT 3 1985

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Cover Photo

Reference stand 20 on the H.J. Andrews Experimental Forest is characteristic of the *Pseudotsuga menziesii/Holodiscus discolor*/grass plant community, *Colomia heterophylla* phase, that was sampled in this study.

Abstract

Means, Joseph E.; Helm, Mary E. Height growth and site index curves for Douglas-fir on dry sites in the Willamette National Forest. Res. Pap. PNW-341. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 17 p.

Equations and curves are presented for estimating height and site index of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) on hot, dry sites in the Willamette National Forest in western Oregon. The equations are based on the dissected stems of 27 trees. The curves differ from those previously published for Douglas-fir. Instructions are presented for their use.

Keywords: Increment (height), site index, Douglas-fir, Oregon (Willamette National Forest).

Research Summary

This study provides height growth and site index curves for Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) on hot, dry sites in the Willamette National Forest in western Oregon. Stems of 40 trees were dissected; 27 of the trees were suitable for construction of height growth and site index curves, and they provided 505 observations of height, site, and age.

Smoothed height growth curves developed from these data were compared with published Douglas-fir height growth curves. Because the published curves could not adequately describe height growth patterns of these trees, new height growth and site index curves were constructed.

Four estimating equations for height growth and three for site index were fitted by use of weighted least squares regression, and site index and height were constrained to be equal at index age, 100 years. The equations with the best fit to the data across the ranges of age and site index were chosen as the final models. The resulting curves differ from those previously published for Douglas-fir.

Instructions for using the equations are presented.

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Introduction

In the western Cascade Range of Oregon and Washington, height growth and site index curves are available for Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) on mesic, midelevation sites (McArdle and others 1961, King 1966), and on upper slopes near the cool extreme of its range (Curtis and others 1974b). No height growth or site index curves have been available, however, for Douglas-fir near the relatively hot, dry extreme of its range in the western Cascades. Height growth of Douglas-fir is slower initially but is more prolonged on such dry sites than on moister sites (Means 1980), and as a result volume growth follows a similar trend. Thus, available site index curves (for example, McArdle and others 1961, King 1966), yield tables (for example, McArdle and others 1961, Curtis and others 1982), and height growth curves in stand growth simulators (for example, DFSIM by Curtis and others 1981) are not applicable. The objective of this study was to construct height growth and site index equations for Douglas-fir on hot, dry sites in the Willamette National Forest in Oregon.

Curves that reach well beyond 200 years are needed for estimating site index for old stands and for estimating height at advanced ages to evaluate the effects of management of stands for old-growth characteristics.

Several methods have been used in constructing Douglas-fir height growth and site index curves. McArdle and others (1961) built height growth curves from many one-time observations of height and age, fitting a mean guide curve, then making other curves proportional to the guide curve. This technique, however, includes several sources of significant error that can be eliminated by using stem dissection data (Curtis 1964). King (1966) used stem dissection data to construct height growth curves for Douglas-fir with height as the dependent variable and then used these curves to estimate site index. Site index estimating equations, however, should be fit with site index as the dependent variable, and height growth estimating equations should be fit with height as the dependent variable (Curtis and others 1974a). Curtis and others (1974b) built upper-slope Douglas-fir height growth and site index curves in this way. Dahms (1975) built on this basic idea by first fitting, for decadal ages, linear regressions to estimate site index ($SI = a0 + a1\ HT$) and height ($HT = b0 + b1\ SI$), then building age back into the models by defining the slopes of these regressions and the mean height curves in terms of age; Dahms worked with lodgepole pine (*Pinus contorta* Dougl. ex Loud.). Cochran (1979) used Dahms' technique to build curves for Douglas-fir in eastern Oregon and Washington. Monserud (1984) found Dahms' technique suitable as a first step in deriving a site index estimating equation, but inferior to a logistic equation for describing height growth of Douglas-fir in the northern Rocky Mountains. As a final step, Monserud (1984) eliminated highly correlated terms from the site index equation without degrading model fit. The equation forms used for Douglas-fir by the above investigators were examined in this study.

Field Methods

Study Area

This study was a component of a larger study in the Detroit, Blue River, McKenzie, Oakridge, and Rigdon Ranger Districts of the Willamette National Forest (Means 1980). Trees were cut in all these Districts except Detroit, where dry coniferous forest is relatively limited in extent, so suitable sampling sites could not be found (fig. 1).

Trees were cut from dry coniferous forests, defined as climax Douglas-fir and incense-cedar (*Libocedrus decurrens* Torr.) and lacking significant (0.1 percent cover) western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) in any size class. These dry-site Douglas-fir community types (Means 1980) are more similar to the *Pseudotsuga/ Holodiscus* type than to any other community type of Dyrness and others (1974).

Tree Selection

Several criteria were used for selecting trees. Candidate trees were dominants or strong codominants with straight boles and no sign of top breakage. Unhealthy crowns, flat or deformed tops, or several conks (or one large conk) were causes for rejection. Candidates were increment bored at breast height. Trees showing periods of suppressed radial growth or significant rot were not used. These criteria for increment cores resulted in rejection of 70 to 90 percent of the trees more than 200 years old, and 30 to 70 percent of the trees 100 to 200 years old that met the exterior criteria. Effects of past fires (scars and resultant butt rot), top breakage, and disease increase with age. Suppressed radial growth was a common cause for rejection, which is not surprising because canopy trees often become established in stands with mature trees (Means 1982). Many plots in stands with canopy trees more than 200 years old contained no trees suitable for dissection (and therefore none suitable for estimation of site index). The high rate of rejection precluded assessment of the potential bias in site index curves caused by changes in the tallest tree on a plot through time (Dahms 1963).

Stem Dissection

The stems of 40 trees on thirty-six 0.1-ha plots were dissected; in general, the techniques of Herman and others (1975) were followed. In most cases cross-section disks were cut at stump height, at breast height (137 cm above ground level), and at 2-m intervals above breast height. Ground level was defined as the mean of the ground levels on the uphill and the downhill sides of the tree. In 1977 whole disks were taken to the laboratory, and narrow (approximately 2 x 2 cm) sections, the length being the distance from the edge to the pith of the disk, were cut with a table saw. Cutting these narrow sections precluded cross-checking ring counts on additional radii. Therefore, in 1978 wider sections (10 to 20 cm) were cut from disks in the field with a chain saw; and whole disks were usually collected at stump and breast height.

Data Preparation

Ring Counting

The narrow sections from trees cut in 1977 were prepared by sanding. The wider 1978 sections were prepared with a belt sander if the wood was dry or with a "Surform"[1/] plane if the wood was moist. Narrow rings (less than about 1 mm) were sanded and were counted under a binocular microscope with variable magnification. Maintaining standing water along radii improved our ability to distinguish rings but was seldom done because it was difficult to sustain for more than a minute. Usually two radii were counted at each disk height.

[1/] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

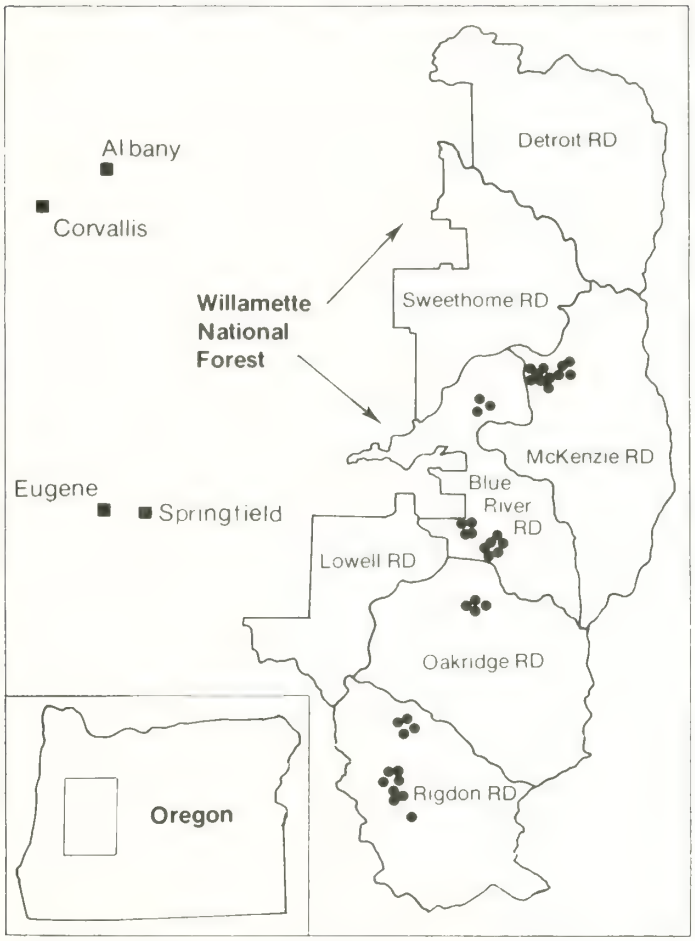

Figure 1.—Locations of sample trees (●) in the Willamette National Forest (RD is Ranger District)

Data Cleaning and Screening

Height versus age was then plotted for each tree. Anomalies such as abrupt changes in height growth rate were often corrected by recounts or counts of new radii on whole sections. A program written in FORTRAN 77, STEM, was used to plot height over age and height growth rate for each tree and to calculate (by linear interpolation) heights at decadal ages for fitting height growth and site index models.

Ten trees showed suppressed height growth early in life or had isolated periods of relatively slow height growth, indicating significant top breakage or suppression. These were excluded from further analysis. Two trees with breast-height age less than 100 were too young to be used for constructing site curves with an index age of 100 and were also excluded. After these trees were rejected, only one 0.1-ha plot remained with two trees. Height growth curves for these trees did not cross, so their decadal heights were averaged and treated as one tree. The height growth curves of two trees were truncated to eliminate height growth anomalies at advanced ages. The analyses thus were based on 27 trees and 505 observations of: height above breast height, site index (height above breast height at 100 years breast-height age), and decadal breast-height age. These trees are summarized by site index class, breast-height age, and topographic position in table 1, and by dry-site plant community in table 2.

Table 1—Distribution of the 27 Douglas-fir trees used in analyses, by breast-height age, elevation, slope, and aspect for ranges of site index

Stratum	Range of site index (meters above breast height, index age 100)						All site indices
	26-30	30.1-34	34.1-38	38.1-42	42.1-46	46.1-50	
	Number of trees						
Breast-height age (yr):							
100-150			1	5	2	2	10
151-200			1	2			3
201-250	1	2	1	1			5
251-300	2	4	1	2			9
	Years						
Mean age	240	263	200	172	122	112	194
	Number of trees						
Elevation (m):							
500-599	1		1	1			3
600-699	1			2	1		4
700-799	1	5	2	4			12
800-899		1		1	1	2	5
900-999			1	2			3
	Meters						
Mean elevation	631	779	760	776	771	899	767
	Number of trees						
Slope (percent):							
0-20				1			1
21-40	1	2	1	1			5
41-60	2		2	4	1		9
61-80		2		4	1	2	9
81-100		2	1				3
	Percent						
Mean slope	39	62	50	53	58	67	54
	Number of trees						
Aspect (degrees):							
91-180			2	3	1		6
181-270	3	6	2	6		2	19
270-360				1	1		2
Total trees	3	6	4	10	2	2	27

Table 2—Distribution of the 27 Douglas-fir trees used in analyses, by plant community for ranges of site index

Plant community 1/	Range of site index (meters above breast height, index age 100)						All site indices
	26-30	30.1-34	34.1-38	38.1-42	42.1-46	46.1-50	
	Number of trees						
Psme/Hodi/grass:							
Asde phase	1						1
Cohe phase	2		1	1			4
Psme/Hodi-Acci	1		1	2	1	2	7
Psme/Beaq/Dispo	1	2	1	1			5
Lide/Whmo				2			2
Lide/Chum		2	1	3	2		8

1/ Plant communities are described by Means (1980). The species codes are: Acci = Acer circinatum, Asde = Aspidotis densa, Beaq = Berberis aquifolium, Chum = Chimaphila umbellata, Cohe = Collomia heterophylla, Dispo = Disporum spp., Hodi = Holodiscus discolor, Lide = Libocedrus decurrens, Psme = Pseudotsuga menziesii, Whmo = Whipplea modesta.

Analysis

Examination of Available Curves

Because our data set is small (27 trees) it was important to determine as a first step whether new curves were really needed or whether existing Douglas-fir curves would suffice. Toward this end, we compared our height growth curves, smoothed using Heger's (1968) data summarization method (at site indices of 28, 32, 36, 40, and 44 m), with the height growth curves published by Curtis and others (1974b), Monserud (1984), King (1966), and Cochran (1979). Site indices for these curves were chosen so they would cross our curves at their index ages.

The height growth curves of King (1966), Cochran (1979), and Monserud (1984) were consistently biased compared with ours; they had higher values for height before their index age (50 yr) and lower values past this age. At age 120, discrepancies were 2.5 to 3.5 m for Cochran's, 4 to 6.5 m for King's, and 3 to 7.5 m for Monserud's. These discrepancies consistently increased past age 120, especially for Cochran's (1979) height curves which declined past age 180—an extrapolation past his data that extended to 130 years.

Curtis and others' (1979b) upper-slope Douglas-fir height growth curves are closer to ours in a narrow range of moderate site indices (32-36 m), where errors are all less than 2 m (within the range of our data). At low sites indices, however, our dry-site trees grow more slowly initially and more rapidly at advanced ages than do upper-slope Douglas-firs. At high site indices, conversely, our trees grow more rapidly initially, and more slowly later than do upper-slope Douglas-firs. Errors range from -1.5 to 2.2 m for trees less than 100 years old and from -2.7 to 3.0 m for trees older than 100 years. The dry-site Douglas-fir height growth curves are more polymorphic than the curves for upper-slope Douglas-fir.

Because height growth curves derived by Heger's (1968) method differed from those already available, our site index curves for Douglas-fir on hot dry sites would also be different; therefore we decided to build new curves even though our data set was small.

Choice of Index Age

An index age of 100 years at breast height (1.37 m) was chosen because this will probably be near rotation age in managed stands of this type, and the reliability of site index estimates should be better than it would be if a younger index age were chosen. Site index estimates are less accurate when differences between stand age and index age are relatively large, and many dry coniferous forest stands are 100 to 250 years old.

Weighted Regression

All height growth and site index models were fitted by weighted least squares regression since variance was not uniform across the range of ages. The iterative weighting technique of Monserud (1984) was used, in which the weight was the inverse of the variance at each decadal age.

Constraining the Models

Height growth models were constrained so that trees "grown" in computer models will reach a height equal to known site index at index age. For all (except one) height growth models, HT = f(SI,age), height (HT) was constrained to equal site index (SI) at index age by subtracting SI = f(SI,index age) from the height model before fitting, giving HT = SI + f(SI,age) – f(SI,index age) (the model of Curtis and others (1974b) was constrained using the technique they describe). Site index models, SI = f(HT,age), were similarly constrained so that trees measured in the field at the index age would have current height as their site index. Errors up to 0.5 m at index age would occur if equations were not constrained. Constraining typically reduced divergence from Heger's (1968) curves (see below) within the range of most of our data and rarely degraded the fit.

Construction of Height Growth Curves

Heger's curves.—The first step in construction of height growth curves was to fit, individually for decadal breast-height ages, linear regressions of height on site index (Heger 1968) of the form

$$HT = a + b\,SI; \qquad (1)$$

where HT = total height - 1.37 m (height above breast height), SI = HT at 100 yr, and a, b = regression coefficients. A total of 28 regressions were fit, for decadal ages 10 to 280. Examination of the data and residuals showed no curvilinear trends at any age. We constructed height-over-age curves (fig. 2) from this family of 28 regressions and compared them with candidate height growth curves to aid in model selection. Heger (1968) used such curves as height growth curves, but we derived a more general equation because these were unrealistically jagged at advanced ages, and to provide one equation for use in computer programs.

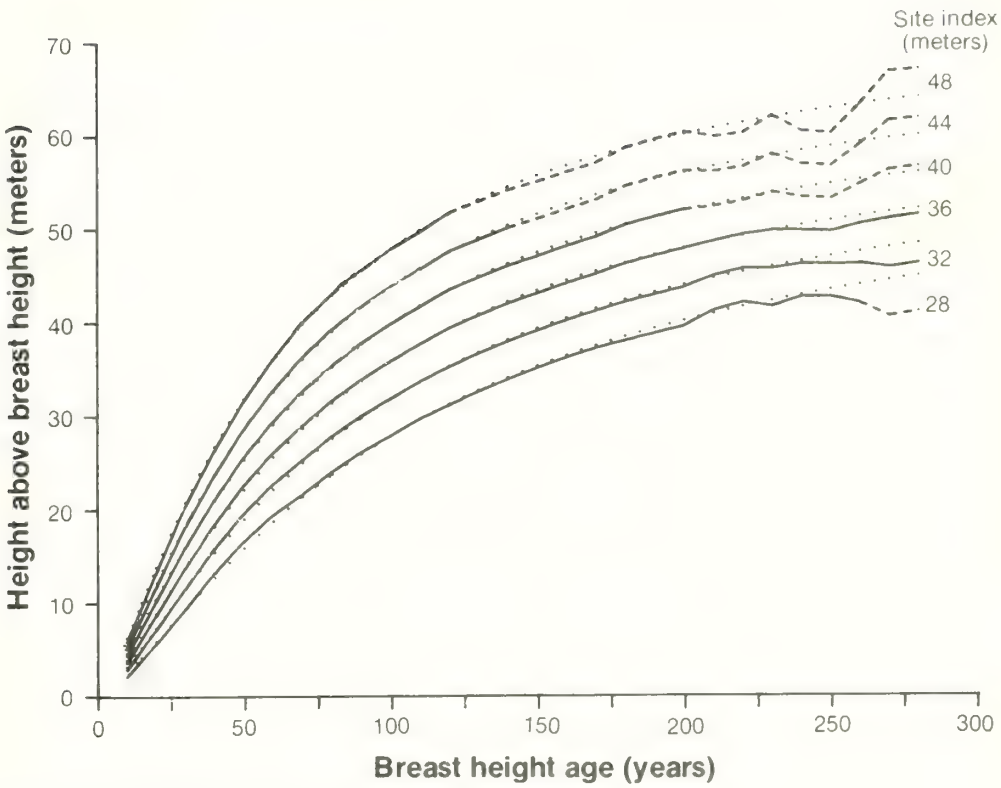

Figure 2.—Height growth curves based on Heger's (1968) family of regressions, equation (1)—solid and dashed curves (dashes indicate points beyond the data); and the final height growth model, equation (6)—dotted curves.

Choosing the height growth model.—Four height growth models were examined. The model used by Curtis and others (1974b), rewritten to express height as a function of site and age, is

$$HT = SI/(a + bA^n + cA^n/SI); \quad (2)$$

where a, b, c, n = regression coefficients and A = breast-height age. The model King (1966) used was examined,

$$HT = A^2/(a + bA + cA^2); \quad (3)$$

where a, b, c = functions of SI. The equation used by Beck (1971) is

$$HT = a\,(1 - \exp(bA))^c; \quad (4)$$

where a, b, c = functions of SI and exp(bA) is the base of the natural logarithm to the power bA. The model form used by Monserud (1984) was also fit,

$$HT = a\,SI^b/(1 + \exp(c + d\,\ln A + e\,\ln SI); \quad (5)$$

where a, b, c, d, e = regression coefficients.

Each model was first fit to the smoothed height over age curves derived by Heger's (1968) method, equation (1). At all but the lowest site index levels, model (5) underestimated height at low ages and overestimated it at high ages so it was not examined further. The remaining models were fit to the decadal heights and ages, and they gave nearly identical fits—standard errors of the estimates (SEE's) ranged from 1.73 to 1.76 m. Examination of residuals showed no problems with bias. Equation (2) was chosen because it had a simpler form; the coefficients of equations (3) and (4) were functions of site index with two or three terms each. Its final form after it was constrained (Curtis and others 1974b) was,

$$HT = SI/(d + b\,A^n + e/SI + c\,A^n/SI); \quad (6)$$

where HT, SI, and A are defined as for equations (1) and (2); d = 0.90031; b = 36.932; e = -11.9659; c = 4433.1; and n = -1.28438; with an SEE of 1.73 m. Height growth curves based on equation (6) and on Heger's regressions, equation (1), are shown in figure 2.

Construction of Site Index Curves

Heger's curves.—The first step in construction of site index curves, similar to that for height growth curves, was to use Heger's (1968) method to fit, individually for decadal ages, linear regressions of site index on height of the form,

$$SI = a + b\,HT; \quad (7)$$

where a, b = regression coefficients. Examination of the data and residuals showed no curvilinear trends at any age. Inverse estimates of height for several levels of site index were calculated and used in plotting these relationships in the traditional height over age format. The linear regressions, equation (7), and the height over age curves were compared graphically with candidate site index estimating equations to aid in model selection.

Constructing and choosing the site index model.—Three site index estimating equations were examined. The first model was a generalized form of equation (7) (Curtis and others 1974b),

$$SI = a + b\,HT; \quad (8)$$

where a, b = functions of breast-height age. Stepwise regression was used to select from many independent variables for describing a and b. Monserud (1984) derived a site index model by first constructing an equation by Dahms' (1975) method, then removing highly correlated terms and recalculating least squares parameter estimates. His final model was the second model examined here:

$$SI = a + b\,(\ln A)^2 + c\,A\,\ln A + d\,HT + e\,HT/A; \quad (9)$$

where a, b, c, d, e = regression coefficients. The third model, constructed by Dahms' (1975) method, involves finding a function of breast-height age (A) for b in equation (8),

$$b = f_b(A), \quad (10)$$

and fitting an equation to mean decadal height (MHT),

$$MHT = f_{mht}(A). \quad (11)$$

When fitting equation (11), we wished to maintain MHT at the same mean site index (MSI = 37.312 m) for all decadal ages. Therefore, when trees dropped out at advanced ages, we estimated MHT from Heger's regressions, equation (7), at SI = MSI. Then MHT was substituted for HT, and MSI (MSI can be considered constant with age since older MHT's were adjusted to it) was substituted for SI in equation (8), which was solved to provide an equation for a:

$$a = MSI - b\ MHT. \tag{12}$$

Substituting equation (11) for MHT in equation (12), then substituting equation (10) for b and the modified equation (12) for a in equation (8), and simplifying, gave a smoothed site index estimating equation of the type used by Dahms (1975):

$$SI = MSI + f_b(A)\ (HT - f_{mht}(A)). \tag{13}$$

This equation was constrained to pass through HT = SI at index age, which eliminated the constant MSI; and new parameters were estimated by least squares to improve its fit.

Height over age curves for each site index model were compared with Heger's curves from equation (7), and plots of the "residuals" (difference) between each model and Heger's curves were examined. Plots of site (predicted, actual, and Heger's) over height and their residuals for alternate decadal ages were also examined. Problems with bias became readily apparent, which facilitated rejection of some models and simplified selection of equation (13) as the final model.

Attempts to reduce the number of coefficients of equation (13), as Monserud (1984) did, markedly reduced the fit, so all fitted coefficients (b-g) were retained. After equation (13) was constrained and simplified it became

$$SI = (b + c\ A + d\ A^{-0.5})\ (HT - 1/(e + f\ A^{g})) + k\ HT + j; \tag{14}$$

where SI, HT, and A are defined as for equations (1) and (2), b = 0.94622, c = -0.00175322, d = 3.6660, e = 0.0168601, f = 2.7676, g = -1.19554, k = -0.137502, and j = 40.470. Site index curves based on this equation are presented in figure 3 and are compared with those based on Heger's regressions, equation (7), in the more familiar inverted form in figure 4.

The final height growth and site index curves are compared in figure 5.

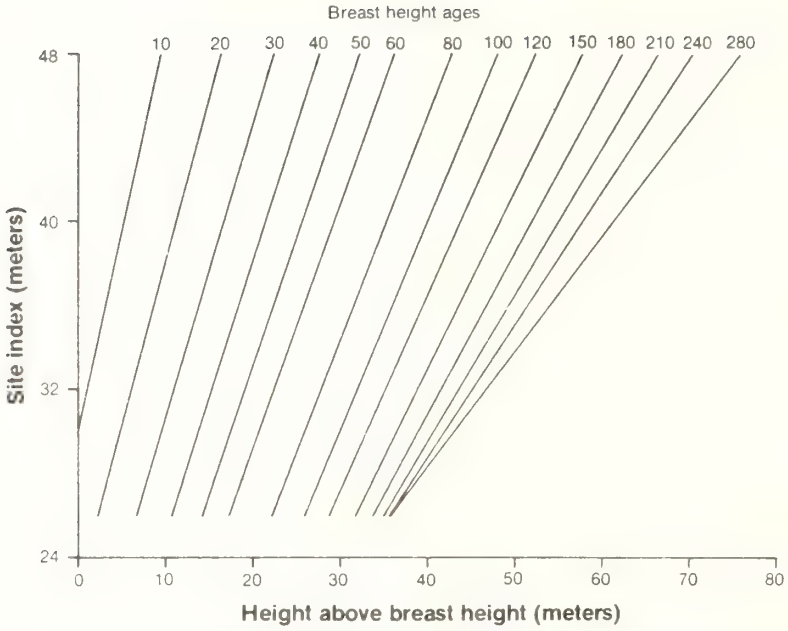

Figure 3.—Final site index estimating curves, equation (14), presented with the dependent variable (site index) on the vertical axis.

Figure 4.—Site index curves based on Heger's (1968) family of regressions, equation (7)—solid and dashed curves (dashes indicate points beyond the data); and the final site index model, equation (14)—dotted curves.

Figure 5.—Comparison of final height growth (solid curves) and site index curves (dashed curves)

Discussion

Comparison With Other Height Growth Curves

The final height growth curves, equation (6), are compared with other height growth curves for Douglas-fir in figure 6. The curves of McArdle and others (1961) for western Washington and Oregon, King (1966) for Washington, Cochran (1979) for eastern Washington and Oregon, and Monserud (1984) for the northern Rocky Mountains all show more rapid height growth at early ages and slower height growth later than do the curves for dry-site Douglas-fir. One important implication is that volume growth in dry-site Douglas-fir stands is initially slower but is more prolonged and maximum mean annual increment occurs later than in the other forest types studied (Means 1980).

Height growth of upper-slope Douglas-fir in the Washington and Oregon Cascade Range (Curtis and others 1974b) is similar to that on dry sites at midsite indices (fig. 6a). At higher site indices, however, height growth on dry sites is initially faster but is slower later in life, whereas at lower site indices it is initially slower but is faster later in life.

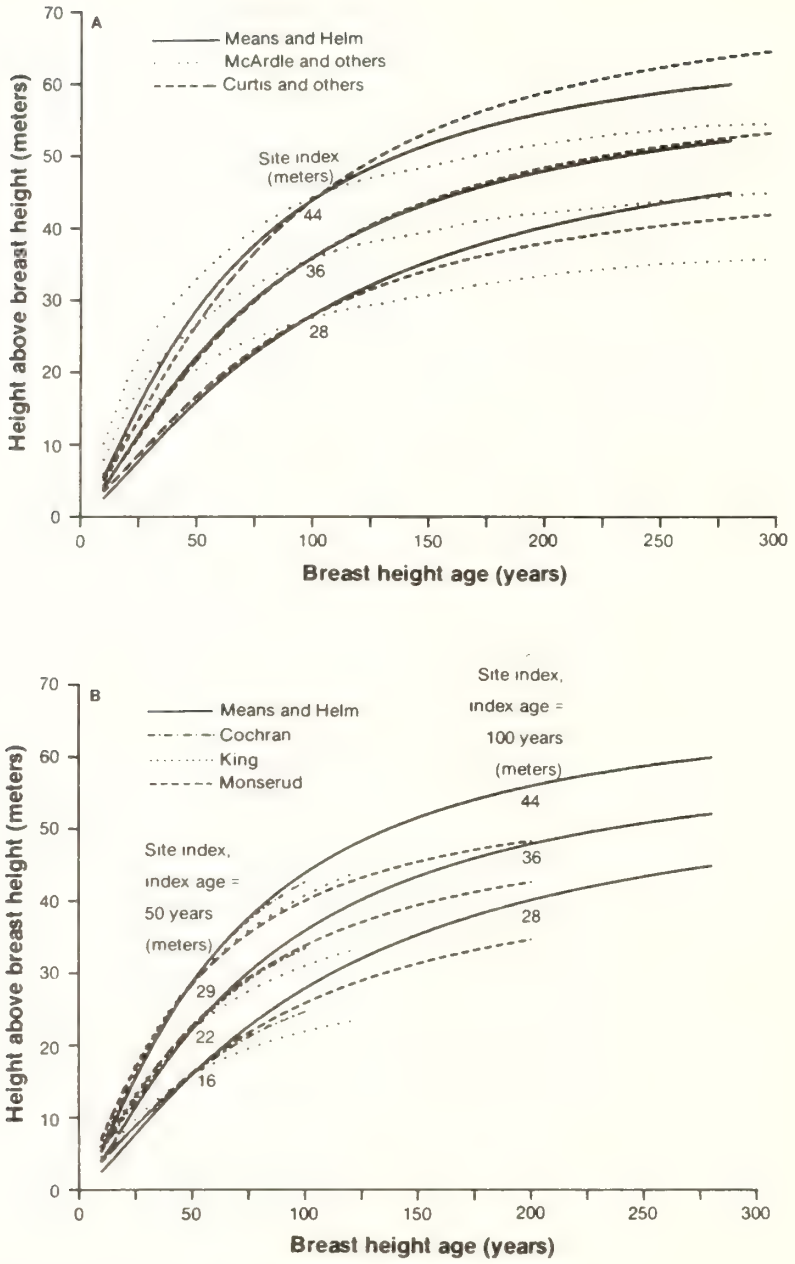

Figure 6.—Comparison of our height growth curves, equation (6), with height growth curves previously published for Douglas-fir. Site indices for these curves were chosen so they would cross our curves at their index ages: A, comparison of our curves with those of Curtis and others (1974b) and McArdle and others (1961); B, comparison of our curves with those of Cochran (1979), King (1966), and Monserud (1984).

Reliability

The reliability of all predicting equations is strongly influenced by the unexplained variation in the data used to build the equations. The variation the final models cannot explain is expressed as the standard error of the estimate (SEE) in figures 7 and 8. Estimates are less reliable when the SEE is greater.

Figure 7.—Standard error of the estimate (uncorrected for the degrees of freedom in the models) for height growth models by decadal age. The solid line is for the final height growth model, equation (6), and the dashed line is for the regressions produced by Heger's (1968) method, equation (1).

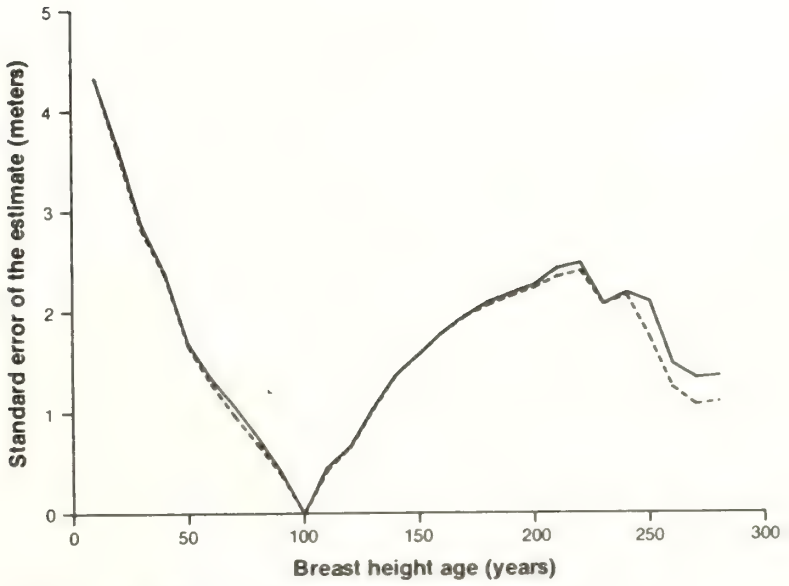

Figure 8.—Standard error of the estimate (uncorrected for the degrees of freedom in the models) for site index models by decadal age. The solid line is for the final site index model, equation (14), and the dashed line is for the regressions produced by Heger's (1968) method, equation (7).

Reliability is reduced by use of the equations beyond the range of the data used to construct them. This range is indicated in figures 2 and 4. Note that no trees older than 139 years at breast height were found at high site indices (table 1). This is reflected in figures 2 and 4 by the jagged appearance of Heger's curves and their divergence from the final model curves at these ages and sites. As a result, estimates at advanced ages and high sites are relatively unreliable extrapolations.

The equations presented here have SEE's similar to those of Monserud (1984) for Douglas-fir in the northern Rocky Mountains, the only other Douglas-fir curves for which this statistic was found. Our SEE's for height growth equation (6) and site index equation (14) are 1.73 and 2.07 m, respectively; Monserud's "tree-about-the-model" errors are 1.55 and 1.89 m, respectively. When data for ages older than 200 years are excluded (as Monserud did), our SEE's (1.53 and 2.06 m) for dry-site Douglas-fir are even closer to his. We, however, included these data to provide a better basis for predictions at advanced ages, and because the data for these ages received low weights in the weighted regression procedure.

We considered Heger's linear equations (1) and (7) to provide the best possible fit, since there was no curvilinear relationship between site and height at any age. The uncorrected sums of squares for error (SSE) of the final models were similar to those for Heger's model (figs. 7 and 8) at all but the oldest ages. Better final models, therefore, could offer only slight improvement unless new variables (for example, soils, nutrients) were considered. We sampled a narrow range of plant communities: the range in site index (28.57 to 48.00 m), only 52 percent of the mean site index (37.31 m), is lower than that of other studies. Thus, environmental variables are unlikely to improve model fit.

Overfitting the data, constructing models that describe meaningless irregularities in the data, can be a problem when models are fit to small data sets such as this one of 27 trees. If this had occurred, it is reasonable to conclude that the SEE's would have been artificially low. The previous comparison with Monserud's (1984) SEE's, however, indicates that this probably did not occur.

Occasionally, straight boles, well-formed tops, and increment cores indicated no problems in height growth, but after the stems were dissected, height growth curves or portions thereof showing height growth suppression were excluded from the analysis. This will not be possible, however, in routine applications of these equations; in particular, estimates of site index for such trees will be low and estimates of height growth (when site index is known from other trees) will be high. Applications of the equations in young stands will not have this bias because all the rejected trees were 117 years at breast height or older. This problem is common (though seldom discussed) to all studies in which data are rejected based on examination of height growth curves after stem dissection. Examination of the height growth curves for trees rejected in this study indicates errors in site index and height will usually be less than 2-3 m.

This source of error will probably be more important in dry-site Douglas-fir communities, where potential site index trees often regenerate after wildfire in stands with surviving trees (Means 1982), and will be less important in community types that are usually even aged. Therefore site index may be less suitable as a productivity index, and the availability of growth models suited to uneven-aged, dry-site stands is probably more critical.

How To Use the Equations

The height growth and site index curves differ in form (fig. 5) and recommended use. The height growth equation was fit with height as the dependent variable. It describes the height growth of trees that attain a specified site index at index age and is appropriate for prediction of height and height growth for stands of given site index, as in construction of yield tables and in stand simulators. The site index equation was fit with site index as the dependent variable. It is a more efficient estimator of site index than is the height growth equation (Curtis and others 1974a) and should be used for estimating site index when age and height are known.

Stand Selection

These equations should be applied to stands in the Willamette National Forest in the Ranger Districts sampled (fig. 1). These equations may be more appropriate than other available equations for use in other Ranger Districts or in adjacent areas (for example, southwestern Oregon); this, however, is not certain. The error associated with this sort of extrapolation probably increases with distance from the areas sampled (fig. 1) and cannot be estimated from data at hand.

Stands should be in dry-site Douglas-fir, defined as Douglas-fir or incense-cedar climax and should lack a significant cover (0.1 percent) of western hemlock in any size class. The above comparisons with other curves indicate that the dry-site Douglas-fir curves are not appropriate for other communities.

Tree Selection

Site index estimates should be based on one or two (when possible) healthy dominants or strong codominants on each 0.1-ha (0.25-acre) plot. Boles should be straight and there must be no signs of past top damage. Candidate trees must be increment bored at breast height, and trees showing suppressed radial growth must be rejected. The desired precision of the site index estimate will determine the number of plots to be taken in a stand.

Top breakage and periods of suppression are likely to be common problems on dry sites where understory trees can eventually reach the canopy. When two acceptable trees occur on a plot, their site index estimates should be averaged. Acceptable site index trees are rare in stands with many trees older than about 200 years, so estimating the site index for these stands may be difficult.

Equations for Total Height in Feet

The following equations are in a form probably most useful to most people. The height growth equation, equation (6), in units of feet is,

$$HT = 4.5 + (SI-4.5) / (d + bA^n + e/(SI-4.5) + cA^n/(SI-4.5)); \quad (15)$$

where HT = total height in feet, A = age at breast height (4.5 ft), SI = total height in feet at 100 yr, d = 0.90031, b = 36.932, e = -39.258, c = 14544.39, and n = -1.28438.

The site index estimating equation, equation (14), in units of feet is;

$$SI = 4.5 + 3.28084((b + cA + d/A^{0.5})(0.3048(HT-4.5) - 1/(e+fA^g)) + k(HT-4.5) + j); \quad (16)$$

where SI, HT, and A are defined as for equation (15), b = 0.94622, c = -0.00175322, d = 3.6660, e = 0.0168601, f = 2.7676, g = -1.19554, k = -0.041911, and j = 40.470.

Acknowledgments

We thank Robert O. Curtis, Robert A. Monserud, Miles A. Hemstrom, David Hann, and Robert Sanders for helpful reviews; Lewis Hass, Jack Booth, Dick Carkin, and Kevin Short for field assistance; and Rod Slagle for computer guidance.

English Equivalents

1 hectare = 2.47 acre
1 meter = 0.3048 foot
1 centimeter = 0.3937 inch

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Means, Joseph E.; Helm, Mary E. Height growth and site index curves for Douglas-fir on dry sites in the Willamette National Forest. Res. Pap. PNW-341. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 17 p.

Equations and curves are presented for estimating height and site index of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) on hot, dry sites in the Willamette National Forest in western Oregon. The equations are based on the dissected stems of 27 trees. The curves differ from those previously published for Douglas-fir. Instructions are presented for their use.

Keywords: Increment (height), site index, Douglas-fir, Oregon (Willamette National Forest).

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Research Paper
PNW-342
September 1985

Soil and Air Temperatures for Different Habitats in Mount Rainier National Park

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DEC 31 1985
PUBLIC DOCUMENTS

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Abstract

Greene, Sarah E.; Klopsch, Mark. Soil and air temperatures for different habitats in Mount Rainier National Park. Res. Pap. PNW-342. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 50 p.

This paper reports air and soil temperature data from 10 sites in Mount Rainier National Park in Washington State for 2- to 5-year periods. Data provided are monthly summaries for day and night mean air temperatures, mean minimum and maximum air temperatures, absolute minimum and maximum air temperatures, range of air temperatures, mean soil temperature, and absolute minimum and maximum soil temperatures. A temperature growth index has also been calculated. Temperature lapse rates are given for one major drainage, Nisqually. The objective is to provide these data for the use of managers, field scientists, and modelers.

Keywords: Temperature (air), temperature (soil), habitat types, Washington (Mount Rainier National Park).

Research Summary

Thermographs were installed at 10 sites in Mount Rainier National Park, Washington. The 10 sites represented different habitat types, the four corners of the park, and a gradient in elevation. Soil and air temperatures were recorded for 2 to 5 years.

The following are calculated for each thermograph site: monthly summaries for day and night mean air temperatures, mean minimum and maximum air temperatures, absolute minimum and maximum air temperatures, range of air temperatures, mean soil temperatures, absolute minimum and maximum soil temperatures.

A temperature growth index (TGI) for the entire year (annual) and for the growing season are computed for each site when data are available. Correlations of annual and growing season TGI to elevation range from 0.59 to 0.99, with a wider spread at higher elevations. Adding a solar radiation factor to each site did not improve regressions between TGI and elevation.

Mean minimum January air temperatures and mean maximum July air temperatures generally decrease as elevation increases. Exceptions occur in cold air drainages and depressions.

Temperature lapse rates for the four sites representing the gradient in elevation are calculated for January and July. These are compared with a long-term (40-year) average for Longmire, a permanent weather station within the park. Winter temperature lapse rates are generally lower than summer rates. This does not hold true for Mount Rainier, perhaps because of the strong maritime influence on winter weather in the park.

Soil temperatures are plotted against elevation for the sites representing a gradient in elevation. A wide variation in January temperatures occurs because of snow depth and duration. Soil temperature lapse rates, like air temperature lapse rates, are greater in winter than in summer.

These data should be useful to managers, scientists, and modelers. Soil and air temperatures, two of the most important environmental values used in ecological studies, are necessary for quantifying the environment and for determining ecological amplitude. They can provide realistic values for ecosystem modeling.

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roduction

Data on air and soil temperatures are among the most important environmental values used in ecological studies. These data are critical to studies of the relationship between biota and environment, such as determination of ecological amplitude and indicator value of specific plants. Soil and air temperature data are important in quantifying the environment indicated by specific habitat types. This kind of data is essential for identifying soils under the current taxonomic classification. These data have recently been used to provide realistic values for devising physiological and ecological models.

Data on temperatures in forest stands and forest soils are rarely reported. Most climatic stations are in openings and do not include soil temperatures. Among forests the least is known about montane and subalpine environments. The only known data sets of this type have been collected for the United States/International Biological Program study site at the H. J. Andrews Experimental Forest, Oregon (Emmingham and Lundberg 1977); Findley Lake in the Cedar River drainage of the Mount Baker-Snoqualmie National Forest, Washington;[1/] and for Mount Rainier National Park, Washington, reported here.

e Study Area

Mount Rainier National Park occupies 96 767 hectares on the western slopes of the Cascade Range in Washington. The dominance of Mount Rainier (4267 m) effectively divides the park into four major drainage systems—Ohanapecosh, White, Carbon, and Nisqually (fig.1).

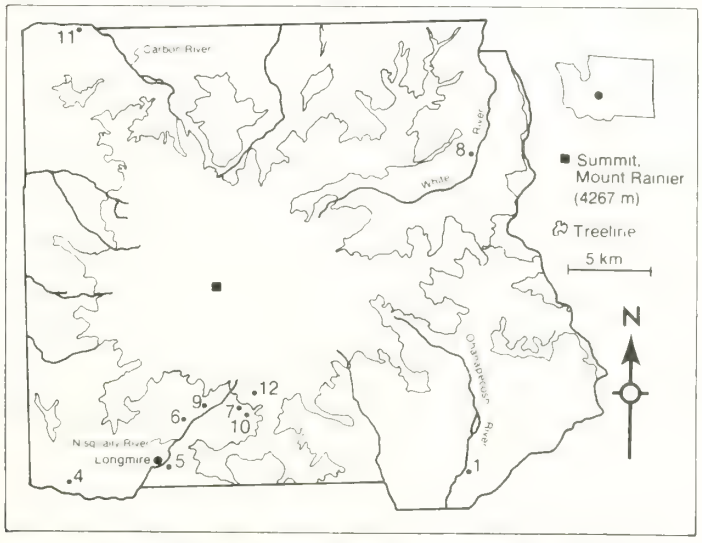

Figure 1.—Mount Rainier National Park. Thermograph sites are numbered. Major drainages are Ohanapecosh, Nisqually, Carbon, and White.

[1/] Unpublished data on file, Dean, College of Forest Resources, University of Washington, Seattle.

A diversity of forest types within the park reflects the varied environments of a rugge mountain system. The forests of the park are dominated by *Pseudotsuga menziesii* within the *Tsuga heterophylla-Thuja plicata* climax (Franklin and Dyrness 1973).[2/] The are three forest zones: *Tsuga heterophylla, Abies amabilis,* and *Tsuga mertensiana* (Franklin and Bishop 1969). Franklin and others classified the forest communities in 1975-79.[3/]

Mount Rainier has a temperate, maritime climate. At lower elevations the rainy seas lasts from early fall through March or April. At higher elevations snow may begin to accumulate by early November and may last through July. Summers are comparative dry. Two weather stations, one at Paradise and one at Longmire, have been measur snow depth and air temperature since the 1920's.

Thermographs were placed in permanent sample plots (sites, 1, 4, 5, 6, 7, 8, 9, 10, 11, located at lower elevations in the four major drainage systems and along a gradient i elevation in the southwest Nisqually drainage (fig. 1). Table 1 shows the permanent sample plot, habitat or forest type, age class, drainage, elevation, and aspect of eac thermograph location. Figure 2 represents these stands in an environmental field. Discussion of the sites and presentation of data start with the Ohanapecosh drainag move counterclockwise to the Nisqually drainage, then up the Nisqually as elevation increases.

[2/] For common names, see "Scientific and Common Names," page 17.

[3/] Franklin, Jerry F.; Moir, William H.; Hemstrom, Miles A.; Greene, Sarah E. Forest ecosystems of Mount Rainier National Park, data on file at Forestry Science Laboratory, Corvallis, OR.

Table 1—Site, age, drainage, elevation, and aspect of thermograph sites at Mour Rainier National Park

Site number and habitat type or open forest	Age	Drainage	Elevation		Asp
	Years		Meters	Feet	
1. Tsuga heterophylla/Achlys triphylla	250	Ohanapecosh	667	2,200	27
8. Abies amabilis/Berberis nervosa	350	White	1050	3,465	30
11. Tsuga heterophylla/Oplopanax horridum	550	Carbon	610	2,013	Fl
4. Tsuga heterophylla/Oplopanax horridum	750	Nisqually	636	2,100	Fl
5. Abies amabilis/Gaultheria shallon	650	Nisqually	945	3,120	26
6. Abies amabilis/Vaccinium alaskaense	750	Nisqually	1053	3,475	21
9. Abies amabilis/Tiarella unifoliata	350	Nisqually	1136	3,750	16
7. Abies amabilis/Rhododendron albiflorum	330	Nisqually	1424	4,700	14
10. Abies amabilis/Erythronium montanum	300	Nisqually	1424	4,700	17
12. Paradise (open subalpine forest)	NA	Nisqually	1660	5,480	20
Longmire Ranger Station	NA	Nisqually	835	2,757	Fl

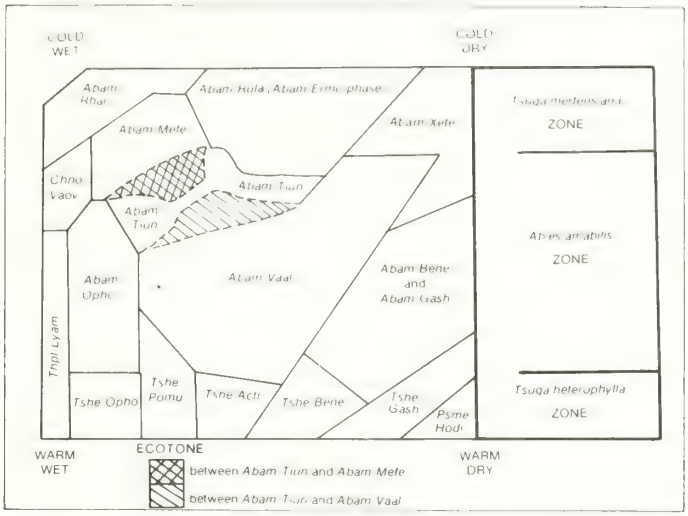

Figure 2.—Distribution of habitat types in relation to an idealized two-dimensional environmental field; horizontal axis represents a moisture gradient and vertical represents a temperature gradient, which (as shown) is closely correlated to elevation and the forest zones on Mount Rainier National Park.

ABAM/BENE = *Abies amabilis/Berberis nervosa* (site 8)
ABAM/ERMO = *Abies amabilis/Erythronium montanum*
ABAM/GASH = *Abies amabilis/Gaultheria shallon* (site 5)
ABAM/MEFE = *Abies amabilis/Menziesia feruginea*
ABAM/OPHO = *Abies amabilis/Oplopanax horridum*
ABAM/RHAL = *Abies amabilis/Rhododendron albiflorum* (site 7)
ABAM/RULA = *Abies amabilis/Rubus lasicoccus* (site 10)
ABAM/TIUN = *Abies amabilis/Tiarella unifoliata* (site 9)
ABAM/VAAL = *Abies amabilis/Vaccinium alaskaense* (site 6)
ABAM/XETE = *Abies amabilis/Xerophyllum tenax*
CHNO/VAOV = *Chamaecyparis nootkatensis/Vaccinium ovalifolium*
PSME/HODI = *Pseudotsuga menziesii/Holodiscus discolor*
THPL/LYAM = *Thuja plicata/Lysichitum americanum*
TSHE/ACTR = *Tsuga heterophylla/Achlys triphylla* (site 1)
TSHE/BENE = *Tsuga heterophylla/Berberis nervosa*
TSHE/GASH = *Tsuga heterophylla/Gaultheria shallon*
TSHE/OPHO = *Tsuga heterophylla/Oplopanax horridum* (site 4)
TSHE/POMU = *Tsuga heterophylla/Polystichum munitum*

The thermograph at site 1 was placed in the Ohanapecosh drainage in a *Tsuga heterophylla/Achlys triphylla* habitat type.[4/] This type is confined to low elevations and is found only on the east side of the park. Soils are tephra deposits with weakly developed podzols. Brockway and others (1983) describe a similar type—*Abies amabilis/ Achlys triphylla-Clintonia uniflora*—which probably occurs on cooler and drier sites, as well as being an *Abies* climax type. An *Abies amabilis/Achlys triphylla* type is also described by Dyrness and others (1974).

[4/] Habitat type descriptions are from Franklin and others (unpublished, see footnote 3) unless otherwise noted. Establishment reports for each permanent sample plot are on file RWU-1251, Forestry Sciences Laboratory, Corvallis, OR, and at Mount Rainier National Park, Tahoma Woods, Ashford, WA.

The thermograph at site 8 was placed in the northeast corner of the park, White Rive drainage, in an *Abies amabilis/Berberis nervosa* habitat type. This type occupies moderately dry, sometimes steep slopes. Colluvium and tephra are the usual soil pare materials. Soils are generally shallow and stony. Brockway and others (1983) do not mention such a type. Franklin (1966) discusses this type, which is comparable to *A. amabilis/Berberis nervosa* (Hemstrom and others 1982) and to *Tsuga heterophylla-A amabilis/Rhododendron macrophyllum/B. nervosa* habitat types found in the Orego Cascade Range (Dyrness and others 1974).

The thermograph at site 11 was placed in the Carbon River drainage, the wettest sectio of the park. This thermograph was in a *T. heterophylla/ Oplopanax horridum* habitat ty which occupies wet benches, terraces, and lower slopes at low elevations in the park Soils are alluvium in origin and lack distinctive horizons. The existence of *Picea sitchensis* in this stand sets it apart from other stands of this type in the park. The Carbo River drainage is one of the few inland sites where this coastal spruce is found.

Thermographs at sites 4, 5, 6, 7, 9, 10, and 12 are in the Nisqually drainage. The thermograph at site 4 was also in the *T. heterophylla/O. horridum* habitat type. This sta had more stems per hectare and less dead and down woody material than did site 1

The thermograph at site 5 was in the *A. amabilis/Gaultheria shallon* habitat type whic occurs primarily in the western half of the park in a transition zone between *T. heterophylla* and *A. amabilis.* Soil parent material is tephra and alluvium. This type is generally found on moderate to steep, southerly exposed, middle and upper slopes, dominated by *Tsuga* and *Pseudotsuga.* It corresponds with Brockway and others' (198 Pacific silver fir/*salal association,* with Franklin's (1966) *A. amabilis/G. shallon* type, with Hemstrom and others' (1982) *A. amabilis/Vaccinium alaskaense-G. shallon* association. Brockway mentions the common occurrence of *A. procera* in these stan

The thermograph at site 6 was in the *A. amabilis/V. alaskaense* habitat type, the mos prevalent community in the park. It is a modal type that occupies environments lackir extremes of temperature and moisture. Because the type is so widespread, various phases occur. Soils are deep, well drained, and commonly podzolic. Though usually found in tephra deposits, the soils may also be developed in colluvial, alluvial, or laha parent material. Brockway and others (1983) describe a Pacific silver fir/Alaska blueberry association in similar terms, though they found *Abies* more dominant i the understory. The type is also described by Dyrness and others (1974), Franklir (1966), and Hemstrom and others (1982).

The thermograph at site 9 was on a steep slope in the *A. amabilis/Tiarella unifoliata* habitat type. This is an herb-rich community found primarily on mesic mountain slopes middle elevations. Soils, developed in tephra or colluvium, are deep and well drainec with no evidence of iron-pan development. Brockway and others (1983) and Hemstr and others (1982) describe this type in similar terms, though they found generally mc shrub cover. Franklin (1966) describes this type for the Mount Adams area.

The thermograph at site 7 was in the *A. amabilis/Rhododendron albiflorum* habitat typ a community found on wet slopes and benches at cold, higher elevations. Snowpack may last into the summer. Soils are usually podzolic with high water tables and saturat conditions most of the year. The overstory is codominated by *Tsuga mertensiana, Chamaecyparis nootkatensis,* and *Abies* spp. Brockway and others (1983) describe

similar community with less emphasis on *C. nootkatensis*, and the addition of *A. procera* and *T. heterophylla*. They mention that the soil profile is generally rocky, with an effective rooting depth of 74 cm. A similar association, *A. amabilis/R. albiflorum/Clintonia uniflora*, occurs in the northern Oregon Cascades (Hemstrom and others 1982).

The thermograph at site 10 was situated in the wet and cold *A. amabilis/Erythronium montanum* phase of the *A. amabilis/Rubus lasiococcus* habitat type. Soils in this phase are developed in tephras. Soil profiles vary from little profile development to strong horizons. Brockway and others (1983) do not mention a similar phase or association. The only close type is described by Fonda and Bliss (1969) for similar stands in the northeast corner of the Olympic Peninsula.

The thermograph at site 12 was at Paradise in open subalpine forest of *A. lasiocarpa*. No habitat type is described for these open forests.

ethods

In the spring and summer of 1978, 10 thermographs were installed in permanent sample plots in the park (sites 1, 4, 5, 6, 7, 8, 9, 10, 11, 12). Each thermograph has air and soil probes that provide for a continuous trace of the temperatures on circular charts. The air probe is placed underneath an A-frame shelter (1 m high) to protect it from sun, wind, and rain. The soil probe is buried 20 cm below the soil surface, parallel to the ground. Thermographs run for approximately 30 days between clock windings.

All thermographs were serviced through 1980, and four (sites 4, 5, 6, 7) were serviced through 1982. The thermograph at site 10 did not function correctly until 1979. Thermographs at sites 9, 10, and 12 were buried under heavy snow during much of the winter, and servicing was generally done from May through November. In 1980 the thermograph at site 9 had mechanical malfunctions. The thermograph at site 11 in the Carbon River was serviced on an irregular basis because of lack of available personnel.

The charts are digitized and the data summarized by use of a computer program, CIRC (1981),[5/] that calculates day and night means, ranges, minimums, and maximums for air temperature; average soil temperatures; and cumulative temperature growth index (TGI).

Another computer program, METMEAN, provides monthly summaries of all the data. These programs were adapted for the CPM operating system and Microsoft Fortran 80. Programs are available from site director at the H. J. Andrews Experimental Forest, Blue River, OR 97413.

Daily data are too voluminous to publish. They are available from Data Bank Manager, Forest Science Department, Forestry Sciences Laboratory, Corvallis, OR 97331.

From Cleary and Waring's (1969) temperature summing algorithm, daily TGI values are summed over each growing season for every site. The TGI allows comparisons among stands based on a model of how average daily soil temperature and average daylight air temperature affect growth of Douglas-fir seedlings.

[5/] Bierlmaier, Fred. CIRC. Blue River, OR: H. J. Andrews Experimental Forest; 1981.

Growing season, as defined by Cleary and Waring (1969), is the period when new ce are produced by the secondary cambium. This stage includes the development of ne foliage and the later phase when only secondary cambial activity occurs. To determi this in the field is a painstaking process. After much work in the Siskiyou Mountains a in the greenhouse, Waring feels that the growing season safely begins when soil temperatures have remained at 4°C or above for 7 consecutive days.[6/] In the Siskiyo the growing season ends in mid-September. Soil temperatures do not drop, rather da length decreases sufficiently to inhibit growth. A small amount of annual cambial gro (<5 percent) may occur after this. Because the park is at a latitude of 46½°N compa to 42½°N for the Siskiyous, we used mid-September as a conservative estimate for t end of the growing season.

Lack of personnel, inaccessibility of several of the sites, and occasional mechanical malfunctions resulted in missing data for some sites. Few gaps occur for the sites in Nisqually drainage. The largest gaps are found at site 11 because of irregular servici and at the higher elevation sites (9, 10, 12). Most of these latter gaps occur in the winte months, not in the growing season. Because TGI requires that soil and air temperature be measured daily, the values for missing data had to be estimated.

To fill these gaps, data from thermographs at similar elevations and aspects were compared by use of regression analysis. The best r^2's (usually greater than 0.80) we chosen, and the regression equations were used to fill in the missing data. New summaries and cumulative TGI's were then run.

Temperature lapse rates—the decrease in temperature with increase in elevation—f the sites in the Nisqually drainage were calculated and compared with the long-term (40-year) average at Longmire (U.S. Weather Bureau 1978-82). Correlations betwee Longmire and all Nisqually sites were made for maximum and minimum January and J daily air temperatures from 1978 to 1982. From the resulting regression equations a the 40-year average data for Longmire, the 40-year averages for the Nisqually sites we estimated. Temperature lapse rates were then obtained by regressing the estimated temperatures against elevation. Lapse rates are generally calculated in open stands; f our purposes we used closed canopy stands. Two lapse rates were actually calculat one included site 12 (the open stand), and one excluded it.

Temperature lapse rates for soils in the Nisqually drainage were also determined. Thes were calculated by regressing the mean soil temperatures for 4 years with elevation.

Results and Discussion

Daily Data

Daily data from the thermographs are presented in the appendix as monthly summar for each site and year.

[6/] Personal communication, Richard Waring, Forest Science Department, Oregon State University, Corvallis.

emperature Growth dex

Number of growing season days and growing season TGI's vary from year to year (table 2). Because the actual beginning and end of the growing seasons are not known, especially for contrasting habitats, the calculated TGI's are only estimates. It is also fairly well established that conifers, unlike hardwoods, may continue photosynthesizing during the winter montns if soil and air temperatures are favorable (Emmingham and Waring 1977). Thus, a growing season TGI may tell us more about hardwoods and deciduous herbs and shrubs than about conifers; table 3 shows the annual TGI for the entire year (the total accumulated throughout the year). Photosynthesis is possible any day that does not have freezing temperatures, so total number of frost free days is given for each site in table 4.

Table 2—Number of growing season days and growing season temperature growth index (TGI) for all thermograph sites at Mount Rainier National Park, except 11

	1978 1/		1979		1980		1981 2/		1982	
Site number	No. days	TGI	No. days	TGI	No. days	TGI	No. days	TGI	No. days	TGI
1	121	59.1	133	67.9	141	63.1				
8	121	53.9	133	55.3	136	50.7				
4	122	59.9	138	66.9	147	64.3	141	62.4	124	61.2
5	121	54.0	117	56.5	136	55.4	112	56.6	119	49.8
6	99	43.6	119	53.0	128	52.6	121	57.0	93	45.3
9	95	41.3	98	45.0	125	47.1				
7	99	37.5	98	40.7	125	51.3	103	44.9	80	31.9
10			64	29.0	67	26.5				
12	58	23.1	116	42.6	83	33.0				

1/ Does not represent an entire growing season. Site 10 thermograph was not installed until 1979.

2/ Thermographs for sites 1, 8, 9, 10, and 12 were discontinued.

Table 3—Annual temperature growth index at sites at Mount Rainier National Park

Site number	1978 1/		1979, 365 days	1980, 366 days	1981, 2/ 365 days	1982, 365 days
1	79.8	(230)	96.4	91.8		
8	71.3	(230)	77.6	74.6		
11	3/		77.1	81.7		
4	80.6	(331)	103.8	97.6	100.5	88.6
5	75.8	(231)	94.2	90.0	99.6	67.7
6	63.0	(208)	83.1	86.5	88.4	66.6
9	61.9	(208)	73.4	80.8		
7	51.5	(208)	67.2	83.2	68.7	46.4
10	3/		52.1	47.7		
12	37.0	(167)	65.3	57.8		

1/ Thermographs were installed in late spring of 1978; numbers in parentheses are total number of days for 1978.

2/ Thermographs at sites 1, 8, 11, 9, 10, and 12 were discontinued.

3/ Not operable.

Table 4—Total frost-free days during entire year for each site at Mount Rainier National Park

Site number	1979	1980	1981 1/	1982
1	292	293		
8	251	260		
11	317	342		
4	327	341	352	323
5	314	336	350	283
6	289	319	321	253
9	309	335		
7	263	282	267	207
10	245	267		
12	215	226		

1/ Thermographs at sites 1, 8, 11, 9, 10, and 12 were discontinued.

The TGI's for site 7 in 1980 are somewhat high because of abnormally high soil temperatures recorded for this site, especially from February through May. These hi temperatures increased the length of the growing season and, consequently, the growing season TGI. Each time a new chart is put on the thermograph the soil probe calibrated with a hand thermometer reading at 20 cm in the soil. There were no discrepancies between calibration and thermograph reading so mechanical error can ruled out.

Site 11 data were not always complete because of difficulty of servicing the thermogra Much of the soil data for February and March of 1980 had to be obtained from regressi estimates, so no growing season TGI appears for site 11 in table 2. Soil temperatures the missing data were high, indicating that the growing season would begin on Janu 28. This was highly unlikely; thus, only the annual TGI is shown.

Site 10 has lower growing season TGI's and annual TGI's than does site 12 at Para which is over 182 m higher in elevation. This may be explained by the open, exposed s at Paradise compared with a closed canopy over site 10. Snow melt occurred nearly month later at site 10 than at site 12. Soil temperatures for site 10 are consistently lowe than for site 12.

The correlation of growing season and annual TGI with elevation (figs. 3 and 4) rang from 0.59 to 0.99. The wide spread in data at the higher elevation is not entirely surprising. There is generally more structural heterogeneity in stands at higher elevati than in stands at lower elevation, which partially explains the variance of values for higher sites. The distribution of habitat types on an environmental field (fig. 2) includ the average growing season TGI for 1979 and 1980.

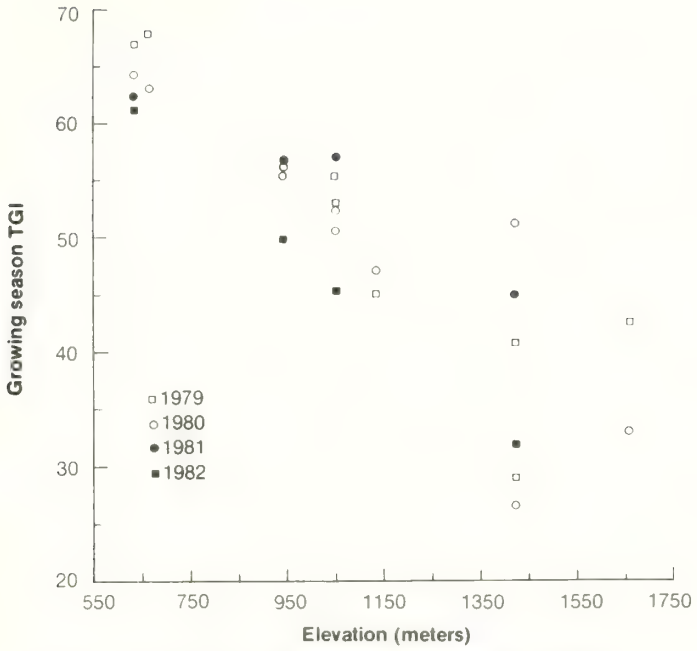

Figure 3.—Growing season temperature growth index for all sites at Mount Rainier National Park, 1979-82.

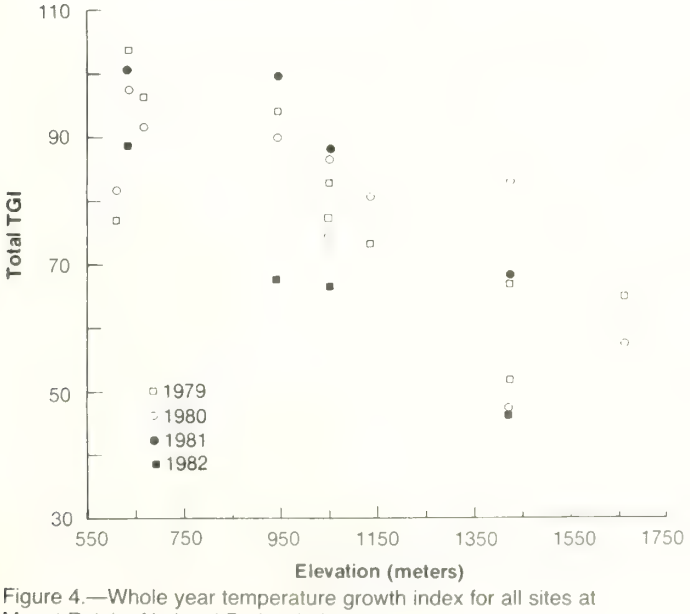

Figure 4.—Whole year temperature growth index for all sites at Mount Rainier National Park, 1979-82.

Variance of annual TGI for sites at low and middle elevations (fig. 4) is greater than that of growing season TGI. Sites at low and middle elevations result in greater TGI throughout the year because of differences in microsite and weather patterns throughout the park. Kaufmann (1984) found considerable local variation in canopy temperature caused by clouds and thunderstorm activity.

So that the regression between TGI and elevation would be improved, multiple regre sions were made adding a solar radiation factor for each site. The solar radiation fact was calculated for Julian day 80 from slope and aspect by the method outlined by Sv (1976). The factor represents the fraction of the potential radiation for a horizontal surface that would reach a sloping site. The single value for the equinox (Julian day 8 was selected because it crudely approximates the cumulative radiation factor for an entire year. The radiation factor had no significant impact on the r^2, which suggested th other factors such as snowpack, cold air drainage, and canopy density were more important. The usefulness of the radiation factor was further diminished because of a significant amount of covariance between elevation and the radiation factor.

Mean Air Temperatures

Mean minimum January air temperatures and mean maximum July air temperatures (table 5) generally decrease as elevation increases. Site 6, however, is 83 m lower th site 9, yet it experienced lower temperatures. Site 6 is in a shallowly depressed, cold drainage, and site 9 is on an east-facing slope, which may account for the difference. Th Ohanapecosh site at 610 m may be on one of the colder sides of the park, as is evidenced by temperatures consistently lower than sites at higher elevations in the Nisqually and the White River drainages.

Table 5—Mean minimum and maximum (January and July) air temperatures for a sites at Mount Rainier National Park

		1978, 1/	1979		1980		1981 2/		1982	
Site	Elevation	July	Jan.	July	Jan.	July	Jan.	July	Jan.	J
No.	Meters	- °C -								
1	667	21.5	-6.6	22.7	-4.5	22.1				
8	1050	20.7	-6.2	21.2	-6.1	20.2				
11	610	3/	-2.3	19.5	-1.8	18.2				
4	636	20.0	-1.4	21.2	-1.7	20.0	4.5	18.6	-.3	1
5	945	19.4	-2.6	21.2	-2.5	20.8	4.8	18.9	-.9	1
6	1053	18.7	-4.3	20.4	-3.9	20.3	2.5	19.3	-1.8	1
9	1136	17.2	-2.6	19.8	-2.1	18.5				
7	1424	18.3	-8.2	18.5	-5.5	18.4	3.3	17.1	-4.7	1
10	1424	3/	-9.5	17.2	-6.7	17.0				
12	1660	20.4	-5.6	16.2	-4.3	22.4				

1/ There are no January values because thermographs were installed in the spring.

2/ Thermographs at sites 1, 8, 11, 9, 10, and 12 were discontinued.

3/ Not operable.

ir Temperature apse Rates

Yearly temperatures for the sites in the Nisqually drainage and estimated long-term averages for the sites based on the 40-year Longmire data are presented in figures 5-10. Each regression line appearing on the six figures displays a closed canopy temperature lapse rate. The lapse rates between January and July temperatures (table 6) are not significantly different by a pair wise T test. There are two sets of lapse rates shown, one including site 12, the open Paradise site, and one without it.

Bamberg and Major (1968) published data for mean January and mean July lapse rates for several areas higher than 1500 m in Montana, Idaho, and Wyoming in the United States and in the Alps in Switzerland. They comment that winter rates are generally lower than summer rates because condensation of moisture decreases the dry adiabatic rate of 1°C/100 m, and because of winter temperature inversions. Lower winter rates do not hold true for Mount Rainier and did not hold for 2 of the 13 areas they cited. The strong maritime influence on winter weather at Mount Rainier may be one explanation for lower winter rates.

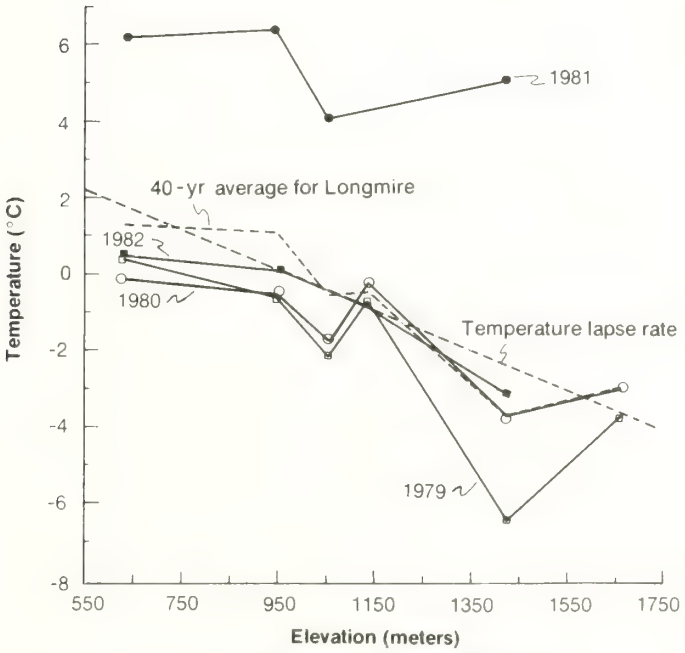

Figure 5.—January mean temperatures for Nisqually sites for 1979-82, the 40-year average, and the temperature lapse rate.

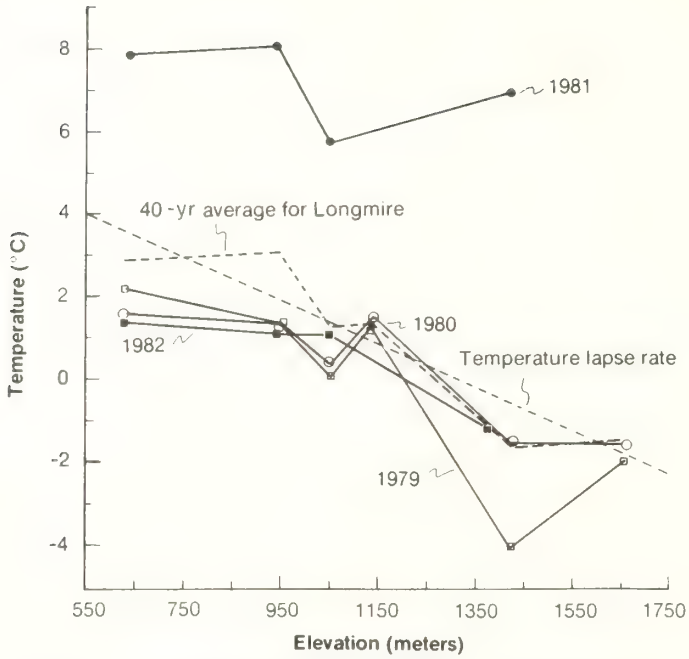

Figure 6.—January mean maximum temperature for Nisqually sites for 1979-82, the 40-year average, and the temperature lapse rate.

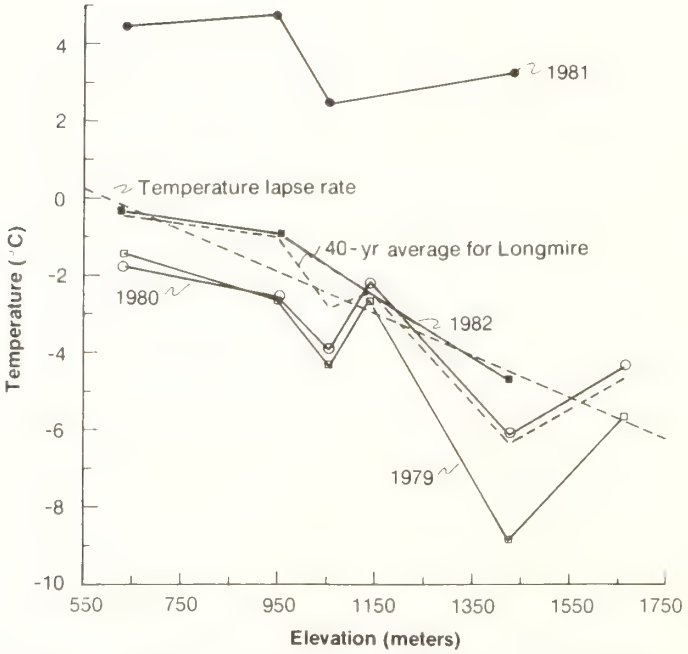

Figure 7.—January mean minimum temperatures for Nisqually sites for 1979-82, the 40-year average, and the temperature lapse rate.

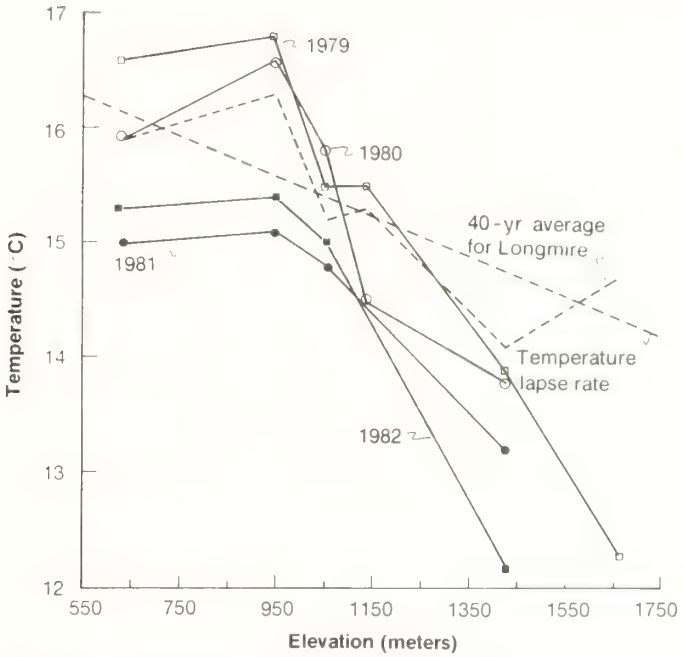

Figure 8.—July mean temperatures for Nisqually sites for 1979-82, the 40-year average, and the temperature lapse rate.

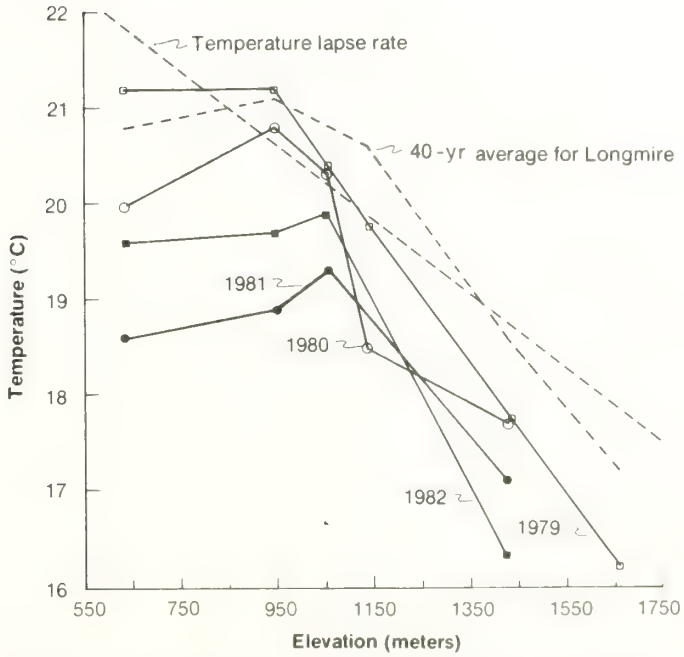

Figure 9.—July mean maximum temperatures for Nisqually sites for 1979-82, the 40-year average, and the temperature lapse rate.

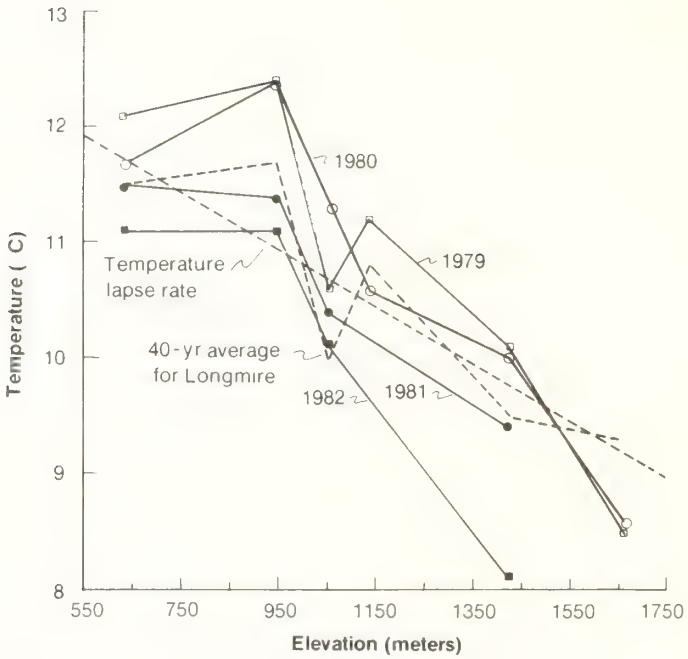

Figure 10.—July mean minimum temperatures for Nisqually sites for 1979-82, the 40-year average, and the temperature lapse rate.

Table 6—Estimated lapse rates for the Nisqually drainage at Mount Rainier National Park

	Lapse rates			
	Air temperature		Soil temperature	
Month	7 sites	6 sites (site 12 excluded)	7 sites	6 sites (site 12 excluded)
	°C/1000 meters			
January minimum	-5.9	-7.9		
January maximum	-5.5	-6.3		
January mean	-5.4	-6.7	-2.46	-2.95
July minimum	-2.5	-2.7		
July maximum	-3.9	-3.2		
July mean	-2.0	-2.7	-1.89	-2.52

oils

The soil probes were placed 20 cm below the surface to avoid the fluctuations in temperature at the ground surface and to register temperatures in the rooting zone (see footnote 5). Root growth also depends on soil temperature.

Figures 11 and 12 plot soil temperatures against elevation for the sites in the Nisqually drainage. The wide variation in January may be related to difference in snow depth and duration. Soil temperatures in January 1981 were unusually warm; Longmire records show 29 snow-free days,[7] as well as higher than normal air temperatures (fig.7). Sites 7 and 10, at the same elevation and similar aspects, show a wide difference in soil temperature. Site 7 on a steep midslope receives more winter radiation than site 10 in a small depression on a gently sloping bench. Site 7 soils are rockier and conduct more heat. Soil temperatures show less variation in summer and generally decrease as elevation increases. Site 10 has colder soil temperatures and snowpack remains longer than at either site 7 or 12.

Soil temperature lapse rates, like the air temperature lapse rates, are greater in the winter than in the summer (table 6). The r^2 for winter was 0.88, and for summer 0.63. Unlike air temperature lapse rates, the soil temperature lapse rates were calculated from 4-year averages.

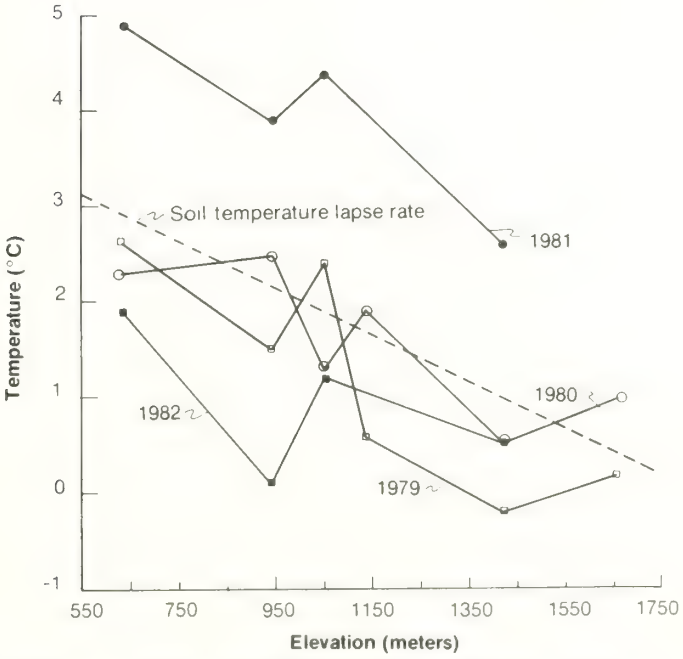

Figure 11.—January mean soil temperatures for all sites for 1979-82.

[7] Unpublished data on file Mount Rainier National Park, Tahoma Woods, Ashford, WA.

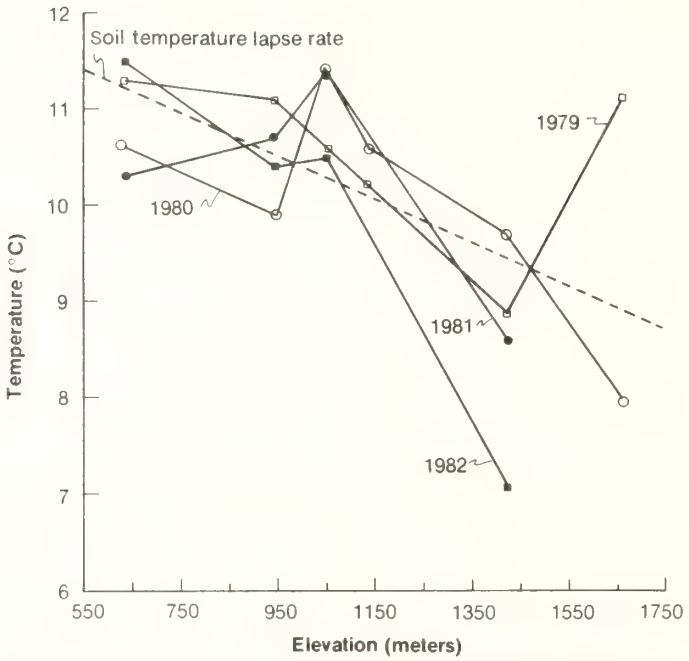

Figure 12.—July mean soil temperatures for all sites for 1979-82.

Conclusion

Because this kind of data takes a long time to gather and is cumbersome to analyze, it seldom appears in the literature. Its importance lies in its usefulness to field scientists an managers in helping to explain the relation between the biota and the environment. Most likely these data will be used by modelers. Modeling formalizes preconceived notions, s the more information available the better the model. These data show, though, that preconceived notions about temperature data are not always reliable; for example, winter lapse rates being lower than summer rates. A better understanding of the relationship between temperature, elevation, topography, and habitat types is needed. The data presented from Mount Rainier provide one more area where these complicate relationships are more clearly understood.

Acknowledgment

We thank the staff at Mount Rainier National Park who braved rain and snow to chang the thermograph charts monthly.

ientific and ommon Names[8/]

Scientific name	Common name
Trees:	
Abies amabilis (Dougl.)Forbes	Pacific silver fir
Abies lasiocarpa (Hook.) Nutt.	Subalpine fir
Abies procera Rehder	Noble fir
Chamaecyparis nootkatensis (D. Don) Spach	Nootka falsecypress
Picea sitchensis (Bong.) Carr.	Sitka spruce
Pseudotsuga menziesii (Mirbel) Franco	Douglas-fir
Thuja plicata Donn	Western redcedar
Tsuga heterophylla (Raf.) Sarg.	Western hemlock
Tsuga mertensiana (Bong.) Carr.	Mountain hemlock
Shrubs:	
Berberis nervosa Pursh	Cascade hollygrape
Gaultheria shallon Pursh	Salal
Holodiscus discolor (Pursh) Maxim.	Creambush rockspirea
Menziesia ferruginea Smith	Rusty menziesia
Oplopanax horridum (J. E. Sm.) Miq.	American devilsclub
Rhododendron albiflorum Hook.	Cascades azalea
Rhododendron macrophyllum G. Don	Pacific rhododendron
Rubus lasiococcus Gray	Blackberry
Vaccinium alaskaense Howell	Alaska blueberry
Vaccinium ovalifolium Smith	Ovalleaf whortleberry
Forbs:	
Achlys triphylla (Smith) DC.	Deerfoot vanillaleaf
Clintonia uniflora (Schult.) Kunth	Queencup beadlily
Erythronium montanum Wats.	Avalanche fawnlily
Lysichitum americanum Hulten & St. John.	American yellowskunkcabbage
Polystichum munitum (Kaulf.) Presl.	Western swordfern
Tiarella unifoliata Hook.	Coolwart foamflower
Xerophyllum tenax (Pursh) Nutt.	Common beargrass

glish Equivalents

0° Celsius	= 32° Fahrenheit
1 centimeter	= 0.4 inch
1 hectare	= 2.47 acres
1 meter	= 3.3 feet
1 kilometer	= 1.6 miles

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[8/] Nomenclature follows Garrison and others (1976).

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Appendix

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 1

DATA YEAR 1978

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
5	17	8.7*	7.1*	12.3*	4.7*	22.0*	1.4*	15.3*	8.9*	10.0*	3.8*
6	30	17.1	12.7	20.4	10.7	29.7	6.9	17.2	9.5	12.2	4.3
7	31	17.6	14.1	21.5	11.4	31.8	7.5	15.5	12.4	14.4	10.5
8	31	17.3	14.8	20.5	12.2	32.6	8.0	19.1	13.9	16.1	12.7
9	30	12.9	11.7	14.8	9.8	22.4	4.2	10.1	12.1	13.8	10.5
10	31	10.1	8.4	13.7	5.2	20.6	.5	13.4	10.5	12.2	6.6
11	30	1.6	1.3	3.7	-1.1	13.7	-6.4	8.9	4.1	7.2	1.6
12	31	-2.8	-3.1	-.9	-5.4	4.3	-17.1	11.5	.7	1.1	.5
YEARLY VALUES:	231	10.4	8.4	13.3	6.0	32.6	-17.1	19.1	9.0	16.1	.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 1

DATA YEAR 1979

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-3.3	-3.8	-.8	-6.6	3.0	-15.5	9.6	.6	3.3	-2.2
2	28	-.2	-.4	1.3	-1.9	5.1	-12.6	9.6	.2	1.1	-1.0
3	31	3.8	1.6	6.2	.0	13.3	-4.5	13.4	.0	.5	0.0
4	30	6.5	4.5	8.8	2.8	21.0	.3	16.0	1.6	5.0	0.0
5	31	12.0	11.0	16.7	7.1	26.8	4.0	19.0	6.3	8.3	5.0
6	30	15.1	13.8	20.0	9.7	29.2	4.5	18.4	9.4	12.2	7.7
7	31	18.4	16.6	23.0	12.9	33.8	5.7	15.9	12.8	15.5	8.8
8	31	17.3	16.1	21.1	12.9	27.9	7.5	16.7	13.5	14.4	12.7
9	30	15.0	15.3	19.5	11.0	27.6	6.5	15.8	12.5	13.3	11.6
10	31	11.4	9.2	13.2	7.3	23.7	1.1	14.7	9.0	11.6	5.5
11	30	4.2	3.5	5.9	1.7	10.6	-3.4	10.1	5.3	6.6	3.3
12	31	4.0	3.5	5.2	2.4	9.5	-1.3	6.8	2.6	3.8	1.1
YEARLY VALUES:	365	8.7	7.6	11.7	5.0	33.8	-15.5	19.0	6.2	15.5	-2.2

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 1

DATA YEAR 1980

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-2.1	-2.3	-.0	-4.5	6.4	-15.8	10.9	1.1	2.7	0.0
2	29	2.4	2.3	3.7	.7	5.8	-5.9	6.6	.8	1.6	.5
3	31	1.3	1.6	3.1	.1	9.1	-4.4	6.2	-.3	4.4	-3.8
4	30	8.4	5.6	11.7	3.4	23.2	-.3	16.1	3.8	6.6	1.1
5	31	11.1	9.8	14.6	6.8	25.2	2.1	20.1	6.9	7.7	6.1
6	30	11.1	11.2	14.3	8.2	21.5	4.5	15.4	8.6	10.0	6.6
7	31	16.9	16.4	22.1	12.0	31.9	8.4	16.5	12.0	14.4	10.0
8	31	15.2	14.7	19.3	10.7	28.6	4.4	16.0	12.3	13.8	10.5
9	30	13.4	12.3	16.9	9.3	25.2	5.4	14.0	10.7	12.2	9.4
10	31	10.7	9.0	14.2	6.2	26.9	1.2	15.3	8.6	12.2	6.6
11	30	4.8	3.9	6.4	2.4	13.3	-.8	9.1	4.8	7.7	2.7
12	31	2.6	2.1	3.9	1.2	12.5	-7.8	6.8	1.7	4.8	0.0
YEARLY VALUES:	366	8.0	7.2	10.9	4.7	31.9	-15.8	20.1	5.9	14.4	-3.8

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 4

DATA YEAR 1978

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
5	17	9.3*	6.7*	11.9*	4.5*	19.8*	1.6*	13.6*	5.4*	6.1*	5.0*
6	30	15.5	12.3	19.0	10.2	27.2	5.3	15.3	8.9	11.1	6.1
7	31	16.3	14.4	20.0	11.4	30.4	7.9	15.9	11.7	13.8	10.0
8	31	16.0	14.3	19.2	11.6	31.3	8.4	15.7	14.4	16.1	13.3
9	30	12.3	10.9	13.9	9.3	20.7	2.8	10.5	11.4	13.8	9.4
10	31	10.4	8.9	12.9	6.3	18.6	2.6	9.9	9.9	11.1	7.2
11	30	2.6	2.6	4.3	.5	12.0	-4.9	6.6	4.8	7.2	2.2
12	31	-.4	-1.9	.4	-2.7	4.5	-11.4	6.2	2.9	4.2	1.6
YEARLY VALUES:	231	10.3	8.6	12.8	6.5	31.3	-11.4	15.9	8.9	16.1	1.6

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 4

DATA YEAR 1979

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	.9	.4	2.2	-1.4	4.7	-7.8	7.1	2.6	2.7	2.2
2	28	1.8	1.4	2.7	.1	4.5	-7.8	7.2	1.5	2.7	.5
3	31	4.4	3.6	6.9	1.7	12.7	-1.2	11.4	1.9	3.3	1.1
4	30	5.9	6.2	9.0	3.4	19.4	0.0	14.6	3.5	6.6	2.2
5	31	11.5	11.1	15.4	7.5	25.2	4.6	16.3	7.4	9.4	6.1
6	30	14.1	13.4	18.2	9.4	26.9	5.8	15.5	9.2	10.5	7.7
7	31	17.0	15.8	21.2	12.1	30.4	7.1	16.5	11.3	13.3	8.8
8	31	16.2	15.2	19.5	12.1	24.5	8.4	13.8	13.2	13.8	12.7
9	30	15.1	13.6	17.9	10.7	25.2	7.4	12.9	12.9	13.8	12.2
10	31	10.9	9.9	12.7	7.7	20.2	3.2	10.5	10.9	12.2	8.8
11	30	5.6	5.0	7.1	3.3	12.0	-1.9	6.6	6.5	8.3	3.8
12	31	5.3	5.1	6.5	3.7	10.3	-.6	7.1	3.8	5.0	2.7
YEARLY VALUES:	365	9.1	8.4	11.7	5.9	30.4	-7.8	16.5	7.1	13.8	.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 4

DATA YEAR 1980

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	.2	-.3	1.6	-1.7	7.3	-12.0	7.6	2.3	4.4	1.1
2	29	3.3	2.9	4.5	1.7	8.8	-3.8	4.8	1.8	3.3	1.6
3	31	4.0	3.7	5.3	2.5	9.5	.4	5.5	2.8	3.8	1.6
4	30	8.8	7.2	11.8	4.3	22.0	1.1	13.2	4.8	7.7	2.7
5	31	11.0	9.9	13.8	7.2	25.5	2.5	16.2	7.3	7.7	6.6
6	30	12.0	11.3	14.3	9.1	20.6	5.2	12.2	8.4	9.4	6.6
7	31	16.8	14.3	20.0	11.7	27.1	8.5	13.1	10.6	12.2	8.8
8	31	14.8	13.7	17.7	10.6	26.4	5.1	12.2	10.8	11.6	10.0
9	30	13.4	11.9	15.8	9.3	22.4	4.9	14.9	9.9	10.5	8.8
10	31	10.0	9.5	12.7	6.4	21.2	1.0	10.1	8.5	10.5	6.6
11	30	6.0	5.5	7.4	3.8	13.5	.6	7.7	5.7	7.7	4.4
12	31	4.1	4.1	5.3	2.9	12.6	-4.1	5.2	3.3	6.6	1.6
YEARLY VALUES:	366	8.7	7.8	10.9	5.7	27.1	-12.0	16.2	6.4	12.2	1.1

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 4

DATA YEAR 1981

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	6.6	5.8	7.9	4.5	12.1	1.8	5.4	4.9	6.1	3.8
2	28	4.2	3.5	5.8	2.1	9.6	-3.6	8.0	3.1	3.8	1.6
3	31	6.3	5.5	8.5	3.1	13.5	.1	9.5	4.2	5.0	3.3
4	30	6.6	5.8	8.8	4.4	18.6	.6	9.6	3.8	6.6	2.2
5	31	9.7	8.7	12.2	6.5	22.0	3.1	13.6	6.5	8.8	3.8
6	30	11.3	11.0	13.9	8.4	23.8	5.1	12.8	8.2	9.4	7.7
7	31	15.4	13.9	18.6	11.5	26.5	6.6	13.0	10.3	11.6	8.8
8	31	17.4	18.1	22.5	13.1	30.9	9.3	14.1	12.3	13.8	11.1
9	30	13.5	12.1	16.5	9.5	26.7	5.2	12.4	10.7	12.2	8.3
10	31	7.9	7.4	10.1	4.9	15.9	2.4	9.1	7.1	8.8	6.1
11	30	6.1	5.4	7.5	4.0	13.1	-.5	5.8	5.7	7.2	3.3
12	31	2.9	2.5	3.8	1.3	8.4	-1.9	5.1	3.0	3.8	2.2
YEARLY VALUES:	365	9.0	8.3	11.4	6.1	30.9	-3.6	14.1	6.7	13.8	1.6

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 4

DATA YEAR 1982

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	.7	.5	1.4	-.3	4.1	-12.0	7.5	1.9	2.7	1.1
2	28	1.6	1.1	2.9	-.5	7.2	-6.8	7.3	2.1	3.3	1.1
3	31	3.7	2.7	5.3	1.3	12.1	-.1	10.3	2.1	2.7	1.6
4	30	4.7	4.5	7.7	1.8	16.9	0.0	15.1	2.5	3.8	1.6
5	31	9.9	9.0	13.6	5.6	21.7	.5	13.9	5.5	7.2	3.3
6	30	15.3	13.6	19.0	10.8	30.0	4.7	15.0	9.2	11.6	6.6
7	31	16.1	14.2	19.6	11.1	29.1	7.2	14.7	11.5	13.3	9.4
8	31	16.5	15.0	19.9	11.8	26.2	8.0	12.3	12.4	13.3	11.6
9	30	13.4	12.4	16.2	9.5	25.3	4.4	11.2	12.9	14.4	11.6
10	31	8.2	8.6	10.6	6.0	14.8	1.3	7.6	10.4	11.6	8.8
11	30	3.3	3.5	4.8	1.9	10.4	-1.2	5.8	4.8	8.8	1.6
12	31	2.9	2.5	4.0	1.2	8.9	-2.3	6.9	2.0	3.3	1.1
YEARLY VALUES:	365	8.1	7.4	10.5	5.0	30.0	-12.0	15.1	6.5	14.4	1.1

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 5

DATA YEAR 1978

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
5	17	8.8*	6.6*	11.5*	4.4*	20.8*	0.0*	13.0*	4.3*	5.0*	0.0*
6	30	13.9	11.5	17.5	9.1	27.8	4.2	14.1	7.7	9.4	5.0
7	31	15.9	13.8	19.4	11.1	31.6	7.0	14.0	10.9	13.3	8.3
8	31	15.8	14.7	19.3	12.0	34.4	8.2	13.9	12.0	13.3	11.1
9	30	11.7	10.7	13.6	9.2	22.6	4.0	14.6	10.6	11.6	9.4
10	31	11.3	10.0	14.0	7.4	21.7	2.3	11.6	10.1	11.1	8.3
11	30	3.1	2.5	4.6	.7	13.3	-3.9	9.0	5.3	8.3	2.2
12	31	-1.3	-1.7	.1	-3.6	4.7	-14.9	10.4	1.8	2.2	1.1
YEARLY VALUES:	231	10.0	8.6	12.6	6.4	34.4	-14.9	14.6	8.1	13.3	0.0

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 5

DATA YEAR 1979

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-.2	-.9	1.4	-2.6	4.5	-10.7	10.5	1.5	2.2	1.1
2	28	1.2	.7	2.3	-.6	4.4	-7.6	7.2	1.2	1.6	1.1
3	31	4.7	3.4	6.7	1.9	13.0	-2.2	9.1	.9	1.6	.5
4	30	5.2	4.9	7.5	2.8	19.1	0.0	12.5	1.5	3.8	.5
5	31	10.6	9.9	14.6	6.8	25.9	2.6	16.8	5.1	7.2	3.8
6	30	13.9	12.1	18.0	8.9	27.1	5.3	14.4	8.7	10.5	6.1
7	31	17.2	15.5	21.2	12.4	31.8	4.6	14.1	11.1	12.7	9.4
8	31	15.7	14.8	19.0	12.0	26.0	9.0	12.3	12.0	12.7	11.6
9	30	15.3	13.7	17.9	11.0	27.4	6.6	12.5	11.9	12.2	11.1
10	31	11.1	10.1	13.0	8.2	23.7	3.0	9.8	9.8	11.6	6.6
11	30	6.2	5.6	7.6	4.2	14.3	-1.9	6.5	5.9	6.6	5.0
12	31	4.6	4.5	6.0	3.1	11.9	-1.0	9.1	4.0	5.0	3.3
YEARLY VALUES:	365	8.8	7.9	11.3	5.7	31.8	-10.7	16.8	6.2	12.7	.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 5

DATA YEAR 1980

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-.3	-.5	1.4	-2.5	6.4	-12.0	7.7	2.5	3.8	-.5
2	29	4.2	3.9	5.4	2.5	8.8	-4.5	6.0	2.0	2.7	1.6
3	31	3.7	3.2	4.6	2.1	10.3	.1	5.3	1.9	2.7	1.1
4	30	8.7	6.4	11.1	4.8	24.2	.7	13.0	3.3	6.1	1.6
5	31	10.7	9.1	13.2	7.1	24.1	2.7	13.6	6.2	7.2	5.5
6	30	11.9	10.7	14.2	8.9	20.8	4.6	12.1	7.3	8.3	6.1
7	31	17.2	15.2	20.8	12.4	31.3	8.8	13.9	9.9	11.6	8.3
8	31	15.0	13.9	18.0	11.3	28.3	6.9	11.2	9.1	11.6	8.1
9	30	14.2	12.7	16.6	10.3	25.4	5.9	11.4	8.0	8.6	6.9
10	31	12.0	10.3	14.2	8.3	26.1	2.9	10.4	7.8	9.4	6.1
11	30	5.5	4.9	7.0	3.6	14.8	-1.7	7.8	5.0	7.2	3.3
12	31	5.6	5.5	6.9	4.1	13.5	-4.5	6.1	2.9	5.0	1.6
YEARLY VALUES:	366	9.0	8.0	11.1	6.1	31.3	-12.0	13.9	5.5	11.6	-.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 5

DATA YEAR 1981

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	6.8	6.0	8.1	4.8	12.1	.4	6.1	3.9	4.4	2.7
2	28	4.2	3.7	5.9	2.2	10.6	-5.6	8.2	2.1	2.7	1.6
3	31	6.1	5.5	8.1	3.6	15.0	.1	8.5	2.7	3.3	2.2
4	30	5.7	5.7	8.6	3.9	20.2	-1.5	10.5	2.3	3.8	1.6
5	31	8.4	8.2	11.5	6.1	22.8	2.8	13.2	4.1	6.6	2.5
6	30	11.3	10.3	13.6	8.3	24.3	6.1	12.8	8.0	10.0	6.6
7	31	15.9	13.9	18.9	11.4	28.8	6.4	13.4	10.7	12.2	9.4
8	31	20.4	17.2	23.9	14.9	34.0	10.5	14.0	13.2	14.4	11.6
9	30	14.7	12.7	17.2	10.8	29.9	6.0	12.6	11.8	13.3	10.0
10	31	9.0	7.7	10.6	5.9	18.2	2.5	10.1	9.0	14.4	7.7
11	30	6.6	5.7	7.9	4.7	16.6	-.2	8.4	7.1	8.3	5.5
12	31	2.0	1.8	3.1	.8	7.6	-3.0	5.5	1.2	5.0	.5
YEARLY VALUES:	365	9.3	8.2	11.5	6.5	34.0	-5.6	14.0	6.4	14.4	.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 5

DATA YEAR 1982

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	.2	.1	1.1	-.9	4.3	-11.9	7.1	.1	1.9	-.5
2	28	1.1	.5	2.3	-1.1	6.5	-7.2	9.0	-.8	0.0	-1.1
3	31	2.9	1.6	4.0	.8	10.2	-1.8	6.9	-.8	0.0	-1.1
4	30	4.0	2.5	5.9	1.0	13.1	-2.2	9.2	-.2	1.3	-.5
5	31	9.7	6.7	12.4	5.1	22.3	1.2	13.7	4.6	6.4	.5
6	30	15.3	12.5	18.7	10.5	29.9	5.1	15.3	8.3	10.5	5.9
7	31	16.4	13.4	19.7	11.1	30.9	7.3	13.7	10.4	12.2	9.4
8	31	16.1	15.5	19.8	12.1	28.6	7.2	12.1	11.6	12.2	11.1
9	30	13.1	12.2	16.0	9.7	27.5	4.0	11.5	11.0	12.9	10.0
10	31	8.8	8.0	10.6	6.1	19.8	1.8	8.2	8.9	10.0	7.2
11	30	2.6	1.9	3.5	1.0	10.0	-2.7	5.2	4.6	7.2	2.7
12	31	1.1	.7	2.1	-.4	7.4	-4.0	6.6	2.4	2.7	1.6
YEARLY VALUES:	365	7.6	6.3	9.7	4.6	30.9	-11.9	15.3	5.1	12.9	-1.1

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 6

DATA YEAR 1978

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
6	24	10.4*	8.2*	14.1*	5.9*	24.0*	2.2*	17.6*	8.3*	10.5*	6.6*
7	31	14.5	12.2	18.7	9.0	28.5	5.2	16.2	10.7	13.8	8.8
8	31	14.0	12.2	17.6	9.5	31.9	5.4	16.3	12.6	15.5	10.5
9	30	10.0	8.3	12.0	6.5	23.3	.9	12.7	10.0	12.7	7.7
10	31	10.9	9.3	14.4	6.6	23.6	1.1	13.3	9.3	10.5	6.1
11	30	1.5	1.0	3.4	-1.0	13.8	-5.8	9.0	2.9	7.2	-.5
12	31	-3.8	-4.2	-1.7	-6.2	4.2	-17.6	10.8	2.2	3.3	0.0
YEARLY VALUES:	208	8.2	6.7	11.1	4.3	31.9	-17.6	17.6	8.0	15.5	-.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 6

DATA YEAR 1979

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-2.3	-1.9	.1	-4.3	4.2	-11.1	9.7	2.4	2.7	2.2
2	28	-.3	-.5	1.3	-2.4	4.4	-9.9	6.8	2.2	2.7	1.6
3	31	3.4	3.1	6.7	.8	12.9	-6.5	10.9	2.1	2.7	1.6
4	30	4.2	3.2	7.2	1.2	17.0	-1.3	12.7	2.2	2.2	2.2
5	31	9.7	6.5	13.3	4.4	24.0	1.6	17.7	5.4	8.8	2.2
6	30	11.3	11.6	16.7	7.0	26.3	3.3	16.4	7.3	9.4	6.1
7	31	16.1	13.8	20.4	10.6	32.6	3.3	16.3	10.6	12.7	6.6
8	31	14.4	13.5	18.2	10.4	25.8	6.8	13.5	11.4	12.2	10.5
9	30	14.1	13.5	17.9	10.0	28.1	0.0	13.3	10.3	11.6	0.0
10	31	9.5	10.6	13.3	7.8	24.6	2.5	12.2	8.6	10.5	5.5
11	30	4.5	5.0	6.9	2.8	13.7	-3.9	7.3	5.2	6.6	3.3
12	31	3.3	3.3	4.9	1.8	10.4	-2.3	8.8	2.2	4.4	1.6
YEARLY VALUES:	365	7.4	6.9	10.6	4.2	32.6	-11.1	17.7	5.8	12.7	0.0

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 6

DATA YEAR 1980

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-1.4	-1.9	.4	-3.9	6.9	-12.9	11.7	1.3	2.7	.5
2	29	3.6	2.8	5.0	1.5	9.2	-6.8	7.9	1.3	1.6	.5
3	31	2.7	2.0	4.1	.8	9.0	-1.8	7.1	1.5	1.6	1.1
4	30	7.1	4.8	10.3	3.1	21.4	-.1	14.3	1.8	3.3	1.1
5	31	8.5	9.3	13.1	5.8	23.8	2.2	17.8	5.8	7.2	3.8
6	30	10.0	11.1	13.8	7.6	21.8	3.5	15.5	7.8	10.0	5.5
7	31	14.6	16.7	20.3	11.3	30.7	7.7	15.5	11.5	13.8	9.4
8	31	13.3	14.2	17.6	10.0	27.4	5.4	13.4	12.1	13.8	10.5
9	30	12.7	12.8	16.8	9.3	25.5	4.9	13.7	10.9	12.2	9.4
10	31	11.6	8.9	14.2	7.0	26.4	1.2	13.7	9.0	12.2	7.2
11	30	4.9	4.9	7.3	3.3	13.9	-4.8	6.1	4.8	8.3	3.3
12	31	4.2	3.9	6.1	2.4	11.0	-.5	7.6	3.2	7.7	1.6
YEARLY VALUES:	366	7.7	7.5	10.8	4.9	30.7	-12.9	17.8	5.9	13.8	.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 6

DATA YEAR 1981

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	4.7	3.6	5.8	2.5	12.6	-6.3	7.1	4.4	6.1	3.3
2	28	3.1	2.8	5.7	1.0	12.2	-7.3	9.5	2.0	3.3	1.1
3	31	4.9	5.1	8.3	2.2	16.7	-.8	12.0	3.1	3.8	2.2
4	30	4.7	4.3	8.3	2.2	22.1	-4.4	14.5	2.1	5.5	1.1
5	31	7.8	8.3	11.6	5.3	24.4	1.4	14.9	5.3	8.8	2.3
6	30	10.3	9.2	13.1	6.8	25.0	3.9	17.1	8.0	10.0	6.6
7	31	14.6	13.2	19.3	10.4	28.8	3.9	14.4	11.4	13.8	9.4
8	31	19.6	16.2	23.8	13.3	34.4	7.9	14.7	14.2	16.1	11.6
9	30	13.6	12.1	17.0	9.4	31.5	4.5	14.5	11.5	15.0	8.3
10	31	8.3	6.9	10.8	4.7	20.3	1.7	12.0	7.3	8.8	5.5
11	30	5.3	4.8	7.2	3.4	15.9	-1.5	9.5	5.1	7.2	3.3
12	31	.9	.8	2.3	-.3	6.5	-4.6	4.8	1.4	2.2	1.1
YEARLY VALUES:	365	8.2	7.3	11.1	5.1	34.4	-7.3	17.1	6.3	16.1	1.1

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 6

DATA YEAR 1982

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-.1	-.4	1.1	-1.8	5.9	-13.0	7.4	1.2	1.6	.9
2	28	.9	-.1	2.5	-1.8	8.1	-8.0	9.9	.1	1.1	-2.1
3	31	1.5	.4	3.9	-1.3	9.9	-6.1	11.0	-1.3	1.1	-2.9
4	30	4.0	2.6	6.8	.2	17.8	-4.0	13.3	.2	1.1	-2.1
5	31	7.9	5.9	12.4	3.9	21.7	.5	14.4	1.0	2.7	.5
6	30	13.8	11.4	18.3	8.7	28.8	3.4	15.9	7.1	10.0	2.7
7	31	15.7	12.3	19.9	10.1	31.6	5.5	15.1	10.5	13.3	8.3
8	31	15.9	13.8	20.2	10.8	30.6	6.8	15.1	12.2	13.3	11.1
9	30	13.0	10.9	16.2	8.8	28.7	3.2	14.3	10.7	14.7	8.3
10	31	8.0	7.2	10.2	5.2	21.3	-.4	9.6	7.2	11.0	4.4
11	30	2.3	2.2	4.2	.8	10.9	-4.4	6.4	2.6	4.7	1.1
12	31	.1	-.3	1.5	-1.6	8.4	-7.2	7.2	.5	2.2	0.0
YEARLY VALUES:	365	7.0	5.5	9.8	3.5	31.6	-13.0	15.9	4.4	14.7	-2.9

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 7

DATA YEAR 1978

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
6	24	8.7*	9.8*	13.4*	6.0*	24.9*	1.9*	15.1*	6.8*	8.8*	5.5*
7	31	14.4	10.9	18.3	9.0	28.7	3.8	15.2	10.3	12.7	8.3
8	31	13.5	10.8	16.7	8.9	32.5	3.8	15.7	11.8	15.0	8.8
9	30	8.9	7.3	11.0	5.5	25.2	.3	15.8	8.8	11.1	5.5
10	31	10.5	8.2	13.1	5.5	22.8	-2.8	16.5	8.6	10.0	5.5
11	30	.9	.1	2.8	-1.8	14.7	-9.9	9.6	3.1	6.6	1.1
12	30	-5.2	-5.7	-2.9	-8.0	3.0	-22.6	10.1	.9	1.6	.5
YEARLY VALUES:	207	7.4	5.9	10.3	3.6	32.5	-22.6	16.5	7.2	15.0	.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 7

DATA YEAR 1979

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-5.1	-6.3	-3.4	-8.2	1.3	-13.5	13.1	.9	1.1	.5
2	28	-2.1	-2.9	-.8	-4.4	3.7	-13.6	7.4	.7	1.1	0.0
3	31	3.8	2.8	6.1	.3	12.9	-7.9	10.7	.4	.5	0.0
4	30	4.4	2.7	6.4	1.0	16.1	-3.4	10.7	.4	.5	0.0
5	31	8.8	6.6	11.7	4.9	22.2	.9	13.3	.6	3.3	0.0
6	30	11.1	8.6	14.5	6.1	24.1	1.4	14.1	6.6	10.0	3.8
7	31	15.1	13.4	18.5	10.4	29.8	1.7	12.6	10.9	14.4	5.0
8	31	14.1	12.4	17.2	10.0	27.5	7.6	15.5	12.0	13.3	9.4
9	30	13.9	12.3	16.6	9.6	27.1	4.1	14.1	11.1	12.7	9.4
10	31	9.6	8.5	11.6	6.4	23.0	.6	11.6	8.5	11.6	4.4
11	30	4.7	4.6	6.7	2.5	15.6	-5.1	8.0	5.8	7.2	5.0
12	31	3.1	2.7	4.6	1.3	10.5	-4.9	10.7	4.3	5.0	3.8
YEARLY VALUES:	365	6.8	5.5	9.2	3.4	29.8	-13.6	15.5	5.2	14.4	0.0

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 7

DATA YEAR 1980

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-2.8	-3.7	-.8	-5.5	9.1	-15.7	10.3	1.6	3.8	-.7
2	29	3.5	3.0	5.3	.8	9.8	-10.2	10.1	4.0	4.4	3.8
3	31	1.3	.3	2.4	-1.0	7.8	-3.5	7.4	3.8	3.8	3.8
4	30	6.7	5.1	9.1	2.9	19.0	-2.3	13.0	4.0	4.4	3.8
5	31	7.7	6.2	9.9	4.4	19.8	0.0	13.1	5.0	6.1	3.8
6	30	9.1	8.1	11.5	5.9	18.8	1.2	11.7	7.6	10.0	4.4
7	31	15.4	13.2	18.4	10.6	28.0	6.2	13.1	12.6	15.0	10.0
8	31	13.3	11.4	15.8	9.1	25.6	3.6	10.9	12.6	15.0	10.0
9	30	12.2	12.1	16.1	9.3	24.5	3.7	13.6	11.2	13.3	8.8
10	31	10.8	9.7	13.6	7.0	26.9	1.6	14.2	7.7	11.1	5.0
11	30	4.0	3.3	5.6	1.5	16.3	-2.8	9.6	2.9	6.6	1.1
12	31	4.2	3.9	5.8	2.2	15.9	-8.7	7.8	1.3	3.3	.5
YEARLY VALUES:	366	7.1	6.0	9.4	3.9	28.0	-15.7	14.2	6.2	15.0	-.7

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 7

DATA YEAR 1981

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	5.5	4.7	7.0	3.3	13.1	-4.0	6.7	2.6	3.3	1.6
2	28	3.0	2.1	4.9	.0	11.4	-10.7	11.5	1.4	1.6	1.1
3	31	4.3	2.6	6.0	.8	14.1	-3.3	10.4	1.1	1.1	1.1
4	30	3.8	3.7	6.4	.8	18.3	-4.6	12.1	.8	1.1	.5
5	31	6.6	5.6	8.6	3.5	21.7	-.6	12.6	1.9	6.1	.5
6	30	9.0	7.8	11.1	5.8	22.7	2.3	12.3	5.4	7.7	2.7
7	31	14.2	12.0	17.1	9.4	26.9	3.0	12.9	8.6	11.6	4.4
8	31	18.9	15.7	22.0	13.4	32.0	7.3	14.4	12.2	14.4	10.0
9	30	12.7	10.5	15.0	8.3	28.4	1.4	13.6	9.8	13.8	5.0
10	31	6.5	5.1	8.5	3.2	20.0	-.9	12.4	4.6	7.2	1.1
11	30	3.4	2.4	4.7	1.1	16.5	-3.7	12.2	2.8	5.5	1.1
12	31	-1.6	-1.6	-.0	-3.2	5.3	-7.6	7.1	.8	1.6	.5
YEARLY VALUES:	365	7.2	5.9	9.3	3.9	32.0	-10.7	14.4	4.4	14.4	.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 7

DATA YEAR 1982

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-2.6	-3.3	-1.5	-4.7	3.2	-15.9	7.2	.5	1.1	-.4
2	28	-2.1	-3.0	-.6	-4.8	4.6	-12.7	10.3	.3	.5	0.0
3	31	-.5	-1.4	1.4	-3.3	9.9	-6.6	9.3	.3	.5	-.5
4	30	.3	-.4	2.8	-3.1	13.7	-7.8	10.8	.2	.5	0.0
5	31	5.2	4.1	7.5	1.6	16.7	-3.2	10.8	0.0	0.0	0.0
6	30	10.3	8.6	12.9	6.7	21.9	-.4	12.3	2.0	5.0	0.0
7	31	13.3	10.5	16.3	8.1	27.3	2.6	13.9	7.1	12.2	4.4
8	31	14.6	12.0	17.3	9.4	27.5	4.4	12.5	9.2	11.1	7.7
9	30	11.2	9.8	13.7	7.3	25.3	.4	10.5	9.0	11.1	6.6
10	31	5.8	5.3	7.8	3.0	20.6	-4.3	8.8	6.1	10.9	2.2
11	30	1.4	.4	2.6	-.6	8.3	-7.1	5.9	1.8	3.8	-.2
12	31	.0	-.6	1.6	-2.2	7.7	-7.9	6.8	1.1	1.6	1.1
YEARLY VALUES:	365	4.8	3.5	6.9	1.5	27.5	-15.9	13.9	3.1	12.2	-.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 8

DATA YEAR 1978

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
5	16	7.4*	4.7*	11.1*	2.4*	20.6*	-.2*	15.2*	4.8*	6.1*	4.4*
6	30	13.8	11.1	18.2	8.3	26.8	4.5	17.2	8.4	10.5	6.1
7	31	16.4	13.0	20.7	9.9	30.5	6.0	17.3	11.6	14.4	8.8
8	31	15.4	12.4	18.8	9.9	33.7	5.5	18.0	12.0	15.0	10.0
9	30	10.3	8.5	12.1	6.9	22.1	1.4	12.5	9.5	11.6	7.2
10	31	9.9	7.1	12.3	5.2	20.0	-1.1	11.0	8.4	10.0	5.5
11	30	.8	-.3	2.1	-1.9	11.5	-7.5	8.1	3.7	6.6	1.6
12	31	-4.0	-4.5	-2.3	-6.9	1.7	-18.1	9.6	1.8	2.2	1.1
YEARLY VALUES:	230	8.8	6.6	11.7	4.3	33.7	-18.1	18.0	7.7	15.0	1.1

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 8

DATA YEAR 1979

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-2.9	-4.4	-1.2	-6.2	3.6	-11.8	10.3	1.0	1.6	.5
2	28	-.6	-1.5	.7	-3.2	4.7	-11.7	9.5	3.8	6.6	1.1
3	31	3.5	1.5	5.8	-.1	12.1	-7.4	9.7	2.1	6.6	.5
4	30	4.5	2.0	7.0	.5	15.9	-3.0	11.5	1.9	5.5	1.1
5	31	9.2	8.1	14.1	4.3	25.8	.5	18.2	6.4	8.8	5.0
6	30	12.8	11.0	17.4	6.9	26.4	1.7	16.3	8.6	11.1	6.6
7	31	15.7	14.7	21.2	10.1	32.6	2.8	15.4	10.8	13.3	6.6
8	31	14.0	14.1	19.0	9.9	27.6	5.9	17.4	11.0	12.2	9.8
9	30	12.0	12.3	15.7	8.5	26.2	3.9	13.2	10.4	11.6	9.4
10	31	8.6	7.7	11.0	5.3	23.1	-.8	11.4	7.7	9.8	5.0
11	30	2.9	1.7	4.3	.6	11.9	-6.7	6.8	3.8	5.0	2.2
12	31	1.4	1.0	2.8	-.4	8.0	-5.1	9.4	1.9	3.3	1.1
YEARLY VALUES:	365	6.8	5.7	9.9	3.1	32.6	-11.8	18.2	5.8	13.3	.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 8

DATA YEAR 1980

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-3.3	-3.8	-1.5	-6.1	4.7	-16.5	10.1	1.0	1.6	.5
2	29	1.8	1.1	3.2	-.3	7.4	-9.7	8.3	.9	1.1	.5
3	31	.6	.2	2.2	-1.4	6.3	-4.1	6.0	1.0	1.1	.5
4	30	5.3	4.3	8.7	1.4	20.9	-3.2	17.2	3.0	6.6	1.1
5	31	7.3	7.5	11.6	3.9	22.5	-.4	19.4	5.9	7.2	4.4
6	30	9.3	8.0	12.5	5.7	22.1	1.7	17.1	7.2	8.8	5.0
7	31	15.3	12.7	20.2	9.3	30.2	5.1	15.7	10.3	12.7	8.3
8	31	13.7	10.3	17.3	7.7	26.3	1.1	13.9	10.2	12.2	8.3
9	30	11.7	9.6	15.2	7.0	22.3	3.1	14.4	9.0	11.1	7.2
10	31	9.4	7.0	12.2	4.5	25.0	-.9	14.6	7.2	11.1	4.4
11	30	3.1	2.4	5.5	.7	13.6	-3.5	10.6	4.6	6.5	2.7
12	31	3.5	2.9	5.2	1.4	12.2	-7.7	7.4	3.2	4.8	2.2
YEARLY VALUES:	366	6.5	5.2	9.4	2.8	30.2	-16.5	19.4	5.3	12.7	.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 9

DATA YEAR 1978

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
6	24	10.8*	8.8*	13.9*	6.9*	24.2*	3.8*	12.3*	8.5*	10.0*	5.7*
7	31	14.3	12.0	18.0	9.5	28.3	4.2	13.3	10.5	12.7	8.8
8	31	15.0	12.7	17.9	10.8	32.3	6.8	14.1	11.5	14.4	9.4
9	30	10.1	9.0	12.2	7.0	24.3	1.8	13.8	9.3	11.1	7.7
10	31	11.9	9.6	14.4	7.2	22.9	1.2	14.9	9.0	10.0	6.6
11	30	3.2	2.1	5.5	.6	18.3	-5.9	15.5	3.8	7.2	.9
12	30	-.3	-1.2	1.7	-3.3	8.5	-15.4	11.0	1.2	1.6	1.1
YEARLY VALUES:	207	9.3	7.6	11.9	5.5	32.3	-15.4	15.5	7.7	14.4	.9

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 9

DATA YEAR 1979

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-.8	-1.2	1.3	-2.6	8.6	-8.0	8.4	.6	1.1	.3
2	28	.6	.4	2.1	-.8	6.0	-8.1	5.9	.5	.9	-.2
3	31	5.8	5.0	8.1	2.9	14.2	-3.6	9.1	.2	.3	-.2
4	30	6.3	4.8	8.4	3.5	17.1	0.0	10.1	.2	.3	-.2
5	31	10.2	8.0	13.2	6.5	22.5	3.4	12.8	.4	3.0	-.2
6	30	12.4	10.1	15.9	7.7	24.4	3.5	12.9	6.5	10.0	3.5
7	31	16.0	13.7	19.8	11.2	31.9	2.8	13.8	10.2	12.2	7.2
8	31	15.1	12.7	18.0	11.0	26.2	8.8	13.3	11.3	12.2	11.1
9	30	15.0	12.9	17.6	10.3	26.3	5.2	13.0	11.0	12.2	10.0
10	31	10.9	9.4	12.9	7.9	24.5	2.2	10.5	8.8	11.6	4.1
11	30	6.2	6.0	8.6	4.0	16.7	-2.7	8.3	5.6	6.8	4.4
12	31	3.6	3.6	5.2	2.2	11.9	-3.0	10.7	3.1	4.4	2.2
YEARLY VALUES:	365	8.5	7.1	11.0	5.4	31.9	-8.1	13.8	4.9	12.2	-.2

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 9

DATA YEAR 1980

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-.6	-.5	1.6	-2.1	10.9	-9.8	8.1	1.9	3.5	-.9
2	29	5.5	5.1	7.5	3.3	11.5	-5.4	8.8	3.7	4.1	3.5
3	31	3.6	2.9	4.9	1.9	9.7	-.1	6.4	3.5	3.5	3.5
4	30	8.3	6.8	10.8	4.9	19.7	.8	12.3	3.7	4.1	3.5
5	31	8.6	6.5	11.1	5.2	20.4	.4	12.3	4.9	6.1	3.5
6	30	9.6	8.6	12.2	6.7	19.2	3.6	12.3	6.7	8.9	4.4
7	31	15.0	13.4	18.5	10.6	28.1	7.6	12.8	10.6	14.4	8.8
8	31	13.0	13.3	16.8	10.3	26.8	5.5	10.9	11.0	14.4	10.0
9	30	13.3	12.1	16.7	9.9	24.8	5.7	12.1	10.0	11.1	8.3
10	31	12.1	10.0	14.4	8.1	26.7	3.1	13.7	8.5	11.1	5.2
11	30	5.9	5.3	7.8	3.9	17.3	.4	9.1	2.7	6.2	.9
12	31	6.2	5.8	7.9	4.4	16.9	-4.2	7.8	1.1	3.0	.3
YEARLY VALUES:	366	8.4	7.5	10.9	5.6	28.1	-9.8	13.7	5.7	14.4	-.9

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 10

DATA YEAR 1979

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-6.3	-8.6	-4.7	-9.5	0.0	-15.1	13.3	-1.3	0.0	-1.6
2	28	-3.2	-4.9	-2.1	-5.5	2.4	-15.2	7.6	-1.5	0.0	-2.0
3	31	2.8	1.4	4.8	-.5	11.6	-9.2	10.6	-1.7	0.0	-2.0
4	30	3.4	1.2	5.1	.2	14.8	-4.5	10.0	-1.7	0.0	-2.0
5	31	8.0	5.4	10.5	4.2	21.0	0.0	12.5	-1.5	.9	-2.0
6	30	10.0	7.7	13.0	5.5	22.9	.6	13.6	2.9	4.7	1.1
7	31	13.8	12.9	17.2	9.8	29.0	.5	11.4	6.8	10.0	2.2
8	31	14.8	12.7	17.0	10.8	25.3	8.1	12.9	8.7	9.4	8.3
9	30	13.5	12.2	15.8	9.3	25.3	3.6	12.6	8.4	10.0	7.2
10	31	9.0	7.9	10.3	6.0	21.4	0.0	9.2	6.2	8.8	3.3
11	30	2.9	2.0	4.5	.8	12.4	-6.0	6.9	2.9	3.3	2.7
12	31	2.1	1.3	3.3	.5	9.2	-6.1	10.5	1.7	2.3	1.3
YEARLY VALUES:	365	6.0	4.3	7.9	2.7	29.0	-15.2	13.6	2.5	10.0	-2.0

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 10

DATA YEAR 1980

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-3.9	-5.8	-2.2	-6.7	7.8	-17.5	10.5	-.6	1.3	-2.6
2	29	2.5	1.6	4.0	-.0	8.5	-11.7	9.8	1.5	1.8	1.3
3	31	.2	-1.4	1.1	-1.9	6.5	-4.6	7.1	1.3	1.3	1.3
4	30	5.8	3.9	7.8	2.1	17.8	-3.3	12.4	1.5	1.8	1.3
5	31	6.5	5.1	7.9	4.1	18.6	.3	12.4	.9	1.8	.5
6	30	6.6	6.6	8.8	4.3	16.3	1.7	10.5	1.2	3.3	.5
7	31	13.2	12.4	17.0	9.5	27.4	3.6	12.8	6.8	9.4	3.8
8	31	12.3	10.3	14.5	8.3	24.3	2.7	9.8	7.8	9.4	6.1
9	30	11.7	10.0	13.5	8.0	21.3	3.1	11.7	6.9	8.3	5.5
10	31	9.7	8.4	11.7	6.3	23.6	1.1	11.7	5.8	8.8	3.8
11	30	3.1	2.0	4.4	.8	14.0	-2.7	9.5	1.2	5.0	-1.1
12	31	3.3	2.6	4.5	1.4	14.6	-10.1	7.0	-.9	.9	-1.6
YEARLY VALUES:	366	5.9	4.6	7.8	3.0	27.4	-17.5	12.8	2.8	9.4	-2.6

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 11

DATA YEAR 1979

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-.7	-.9	.5	-2.3	5.0	-9.7	6.9	3.0	5.5	-.5
2	28	1.4	1.2	2.4	.0	5.8	-6.2	5.0	3.0	3.4	2.5
3	31	2.9	3.1	5.3	.9	9.1	-2.4	7.7	1.8	3.3	1.1
4	30	5.8	5.5	7.8	3.6	15.2	.7	8.6	2.8	2.9	2.5
5	31	8.7	8.6	12.2	6.1	21.0	3.6	14.4	3.8	8.8	2.5
6	30	12.6	12.8	16.8	8.9	25.7	3.7	14.4	8.9	10.0	7.7
7	31	14.8	15.9	19.5	11.4	28.3	5.6	12.4	11.4	13.3	8.8
8	31	14.5	15.2	18.0	11.8	23.2	8.8	12.3	12.0	12.7	11.1
9	30	12.4	12.9	15.0	9.9	20.1	5.9	8.0	11.7	12.7	11.1
10	31	8.6	9.2	10.8	6.9	16.0	3.2	7.9	9.7	11.1	7.7
11	30	3.5	4.4	5.5	2.8	9.2	-1.8	6.0	6.3	7.7	4.4
12	31	4.7	4.3	5.9	2.9	11.7	-1.6	7.9	5.4	6.6	4.4
YEARLY VALUES:	365	7.5	7.7	10.0	5.3	28.3	-9.7	14.4	6.7	13.3	-.5

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 11

DATA YEAR 1980

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-.1	-.4	1.1	-1.8	6.9	-10.2	6.1	3.5	5.5	2.2
2	29	5.2	5.7	7.0	3.5	10.4	-3.9	7.5	5.7	6.0	5.5
3	31	3.7	3.6	4.8	2.3	8.9	.6	5.4	5.5	5.5	5.5
4	30	7.4	7.2	9.9	4.7	17.3	1.4	10.4	5.9	7.2	5.5
5	31	9.2	8.5	11.6	6.1	19.8	2.0	12.8	7.2	7.7	6.6
6	30	9.0	9.7	11.7	6.9	17.3	3.8	9.5	8.6	10.5	6.0
7	31	14.7	14.1	18.2	11.0	25.3	7.3	12.4	10.8	12.7	9.4
8	31	13.2	12.2	15.8	9.9	23.0	5.4	10.2	11.6	12.2	10.9
9	30	11.0	11.4	13.5	8.7	20.7	6.2	8.6	10.7	11.3	9.4
10	31	8.3	8.5	10.8	5.7	19.0	.7	7.3	8.9	11.1	7.2
11	30	5.4	5.5	6.9	3.9	12.6	.6	5.9	5.6	8.8	3.4
12	31	5.7	6.4	7.4	4.4	15.1	-2.9	6.7	3.6	5.1	2.9
YEARLY VALUES:	366	7.7	7.7	9.9	5.4	25.3	-10.2	12.8	7.3	12.7	2.2

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 12

DATA YEAR 1978

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
7	14	16.6*	13.2*	20.4*	10.9*	25.3*	7.0*	15.1*	8.8*	10.0*	7.2*
8	31	13.4	11.2	15.6	9.0	29.3	4.2	11.8	10.0	12.7	8.3
9	30	7.2	6.3	9.2	4.0	22.7	-1.7	13.5	6.7	9.4	4.4
10	31	9.7	7.3	11.8	5.0	20.8	-3.0	16.0	6.9	22.7	4.4
11	30	-.4	-1.8	1.7	-3.5	15.7	-12.4	12.5	2.3	4.4	1.1
12	31	-3.5	-4.1	-2.4	-5.5	2.8	-12.0	8.6	1.1	1.1	1.1
YEARLY VALUES:	167	6.2	4.6	8.3	2.6	29.3	-12.4	16.0	5.7	22.7	1.1

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 12

DATA YEAR 1979

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-4.3	-4.2	-1.9	-5.6	1.6	-11.9	7.6	.2	1.1	-.3
2	28	-2.8	-2.8	-.6	-3.7	1.4	-11.9	7.7	-1.0	.1	-1.9
3	31	.3	-.6	4.1	-2.1	10.5	-5.1	13.0	-.7	.7	-1.4
4	30	2.1	2.1	6.3	-.4	17.9	-3.8	16.8	.9	3.8	-.3
5	31	8.7	7.1	13.4	3.9	24.2	.9	18.8	4.5	6.4	3.3
6	30	11.4	9.2	16.1	5.6	26.1	.8	18.2	6.2	8.8	4.8
7	31	13.9	11.0	16.2	8.5	27.0	.8	12.3	8.8	11.1	5.0
8	31	13.1	10.8	15.3	8.5	23.5	6.3	13.7	10.3	11.1	9.4
9	30	13.5	10.5	19.3	7.8	35.6	1.3	28.0	9.6	11.1	8.3
10	31	9.4	6.7	13.7	4.7	37.7	-1.6	26.3	7.2	10.5	2.2
11	30	3.5	2.1	6.7	.3	21.8	-7.5	18.2	2.8	3.8	2.7
12	31	1.2	1.0	3.1	-.6	8.6	-7.1	10.8	1.7	2.7	1.1
YEARLY VALUES:	365	5.9	4.4	9.3	2.3	37.7	-11.9	28.0	4.3	11.1	-1.9

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

MOUNT RAINIER NATIONAL PARK

METEOROLOGICAL DATA SUMMARY

SITE 12

DATA YEAR 1980

MONTH	NUMBER OF DAYS	DAY MEAN AIR TEMP (C)	NIGHT MEAN AIR TEMP (C)	MEAN MAXIMUM AIR TEMP (C)	MEAN MINIMUM AIR TEMP (C)	ABSOLUTE MAXIMUM AIR TEMP (C)	ABSOLUTE MINIMUM AIR TEMP (C)	ABSOLUTE RANGE AIR TEMP (C)	MEAN SOIL TEMP (C)	ABSOLUTE MAXIMUM SOIL TEMP (C)	ABSOLUTE MINIMUM SOIL TEMP (C)
1	31	-3.0	-3.0	-1.5	-4.3	2.0	-16.0	7.8	1.0	1.6	-.3
2	29	-1.0	-1.3	1.4	-2.1	6.2	-7.7	5.5	-.7	.7	-.9
3	31	-.2	-.4	2.3	-1.3	6.9	-3.4	6.7	.2	1.2	-.9
4	30	5.5	3.1	9.5	.5	20.7	-2.7	15.3	2.1	4.8	.1
5	31	6.5	4.2	8.8	2.3	24.6	-2.5	18.6	2.1	4.8	1.6
6	30	8.2	5.8	12.6	4.2	31.0	-.7	24.3	3.9	6.1	1.6
7	31	15.6	10.9	22.4	8.6	39.3	4.1	30.1	8.0	10.0	5.5
8	31	12.0	9.1	14.7	7.4	32.5	2.3	27.7	8.3	10.0	6.6
9	30	11.1	9.3	13.5	7.1	22.5	2.2	11.5	7.3	8.8	5.5
10	31	9.8	7.8	11.9	5.9	23.5	-.1	12.2	6.1	9.4	3.8
11	30	1.9	1.3	4.4	-.3	15.6	-4.5	10.7	2.3	5.0	.5
12	31	-.0	-.0	2.3	-.9	10.4	-8.0	5.7	.7	3.8	-.9
YEARLY VALUES:	366	5.6	3.9	8.6	2.3	39.3	-16.0	30.1	3.4	10.0	-.9

TEMP = temperature; (C) = degrees Celsius.
Values followed by an asterisk (*) have more than 5 missing days.

*GPO 597 - 448 (191

Greene, Sarah E.; Klopsch, Mark. Soil and air temperatures for different habitats in Mount Rainier National Park. Res. Pap. PNW-342. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 50 p.

This paper reports air and soil temperature data from 10 sites in Mount Rainier National Park in Washington State for 2- to 5-year periods. Data provided are monthly summaries for day and night mean air temperatures, mean minimum and maximum air temperatures, absolute minimum and maximum air temperatures, range of air temperatures, mean soil temperature, and absolute minimum and maximum soil temperatures. A temperature growth index has also been calculated. Temperature lapse rates are given for one major drainage, Nisqually. The objective is to provide these data for the use of managers, field scientists, and modelers.

Keywords: Temperature (air), temperature (soil), habitat types, Washington (Mount Rainier National Park).

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Research Paper
PNW-343

July 1985

NORTH CAROLINA'S Forest Products Industry: Performance and Contribution to the State's Economy, 1970 to 1980

Con H Schallau, Wilbur R. Maki, Bennett B. Foster, and Clair H. Redmond

Abbreviations

States

AL	Alabama
AR	Arkansas
FL	Florida
GA	Georgia
KY	Kentucky
LA	Louisiana
MS	Mississippi
NC	North Carolina
OK	Oklahoma
SC	South Carolina
TN	Tennessee
TX	Texas
VA	Virginia
SO	South
US	United States

Industries

FPI	Forest Products Industry
LWP	Lumber and Wood Products
PAP	Paper and Allied Products
WF	Wood Furniture

Authors

CON H SCHALLAU is a research economist at the Pacific Northwest Forest and Range Experiment Station, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, Oregon 97331. WILBUR R. MAKI is a professor, University of Minnesota, Department of Agricultural and Applied Economics, St. Paul, 55108. BENNETT B. FOSTER and CLAIR H. REDMOND are, respectively, forest economist and economist, USDA Forest Service, Southern Region, State and Private Forestry, 1720 Peachtree Road N.W., Atlanta, Georgia 30367.

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Abstract

Schallau, Con H; Maki, Wilbur R.; Foster, Bennett B.; Redmond, Clair H. North Carolina's forest products industry: performance and contribution to the State's economy, 1970 to 1980. Res. Pap. PNW-343. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 22 p.

Employment and earnings in North Carolina's forest products industry, like those of most Southern States, grew significantly between 1970 and 1980. The forest products industry accounted for a larger share of the State's economic base in 1980 than in 1970. North Carolina had more forest products industry employment than any other State in the South. Moreover, during this period, the State increased its share of the Nation's forest products industry employment and earnings. Pulp and allied products had the highest productivity in 1977 and the largest increase in productivity between 1972 and 1977.

Keywords: Forest products industries, economics (forest products industries), North Carolina.

Preface

North Carolina's forest products industry, like that of most Southern States, experienced significant growth during the 1970's. This resurgence resulted from the increasing size and amount of timber, investment in new plants and equipment, and a growing demand for North Carolina's forest products.

This report briefly describes North Carolina's forest products industry—its composition, location, evolution, and relation to economic activity elsewhere in the State, the South, and the Nation.

Estimates of employment and earnings shown in this report were derived from U.S. Department of Commerce data. All references to dollar amounts are in constant 1977 dollars.

This is one in a series of reports for each of the 13 Southern States. These reports are companions to a forthcoming analysis of the changing roles of the forest products industries of the South and the Pacific Northwest.

Highlights

- In 1980, North Carolina had more employment in the forest products industry than did any other Southern State. The forest products industry was the second largest component of North Carolina's economic base (a State's economic base being comprised of industries producing for export outside the State). Furthermore, the forest products industry was a larger component of the State's economic base in 1980 than it was in 1970.

- In 1980, wood furniture manufacturing was the largest component of the State's forest products industry in terms of employment and earnings. North Carolina accounted for 26 percent of the Nation's wood furniture manufacturing employees and 24 percent of the earnings. During the 1970's, wood furniture and paper and allied products were the fastest growing segments of North Carolina's forest products industry in terms of employment. Paper and allied products was the fastest growing in terms of earnings.

- In 1977, wood furniture manufacturing accounted for the largest share of value added by North Carolina's forest products industry. Paper and allied products, however, showed a significantly greater increase in the rate of growth between 1972 and 1977.

- North Carolina's forest products industry was last in the South in terms of capital productivity (measured in terms of value added, minus payroll, per worker hour). In terms of percentage of change between 1972 and 1977; it tied for fifth place among the 13 Southern States.

- In 1977, paper and allied products had the highest capital productivity in the State's forest products industry and exhibited the greatest increase in productivity between 1972 and 1977.

- During the 1970's, North Carolina increased its share of both the Nation's employment and earnings in the forest products industry.

- In 1980, average earnings in North Carolina's forest products industry were below the average for the Nation's forest products industry. Between 1970 and 1980, the growth in earnings in North Carolina's forest products industry was less than the rate for the Nation's forest products industry.

- Earnings per worker in North Carolina's paper and allied products manufacturing were significantly greater than the earnings in the other segments of the forest products industry.

- In 1980, only two Southern States (Mississippi and Arkansas) were more dependent on the forest products industry than was North Carolina.

- In 1977, the forest products industry in North Carolina produced more value added than did its counterparts in all other Southern States.

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The Forest Products Economy of North Carolina

The State's Workforce

North Carolina's estimated full- and part-time workforce in 1980 was comprised of an estimated 2.9 million employees and proprietors (see appendix tables for sources of employment and earnings data). Unlike most Sun Belt States, North Carolina's workforce grew slightly more slowly between 1970 and 1980 than did the national average (21.3 percent versus 22.3 percent). But total earnings—wage and salary payments and proprietorial income—grew faster than the national average. Measured in constant 1977 dollars, the State's earnings increased by 32.6 percent as compared to 27.4 percent for the Nation. As can be seen in the following tabulation, manufacturing, services, and State and local government were the State's three largest employer categories:

	Percent of total employment, 1980	
Employers	**North Carolina**	**U.S.**
Major industries:		
Manufacturing (including the forest products industry)	28.31	19.15
Services	13.58	18.22
State and local government	12.20	12.56
Retail trade	12.09	14.18
Nonfarm proprietors	6.24	6.58
Agriculture	6.13	4.39
Wholesale trade	4.19	4.97
Construction	4.10	4.08
Transportation, communication, and public utilities	4.03	4.84
Subtotal	90.87	88.97
All other industries	9.13	11.03
Total	100.00	100.00

Components of the State's Economic Base

Along with total employment there is another and perhaps more important way to judge an industry's contribution to North Carolina's economy. For the State's economy to grow and develop, it must attract new dollars so residents can buy goods and services produced elsewhere. The industries that export products and services beyond local boundaries (that is, to elsewhere in the State, to other States, and to the world) and bring in new dollars, constitute the area's economic base. Generally speaking, most manufacturing employment is classified as "economic base" (or "basic"), while service or residentiary employment (for example, barber shops, realty firms, schools, and local government) is primarily geared to producing for local needs. Federal military provides national defense for all the Nation's citizens. Furthermore, taxpayers outside North Carolina help support this activity; consequently, Federal military qualifies as a basic industry.

Residentiary employment is supported by the economic base. Money flowing in provides income for wage earners and entrepreneurs to spend on locally purchased goods and services. In most cases, the economic growth of a region is dependent upon the success of its economic base.

We used the excess employment technique to identify the industries that comprise North Carolina's (or the substate district's) economic base. This approach accepts the national distribution of employment among industries as a norm. Any industry with employment in excess of this norm is considered to be producing for export markets outside the State (or substate district) and is part of North Carolina's economic base. The percentage of North Carolina's excess employment served as an indicator of the State's dependency on a particular industry for generating new dollars from outside the State. (Table 2 shows how excess employment and industry-dependency indicators for North Carolina were calculated.) A particular industry may be basic at the local level but not at the State level.

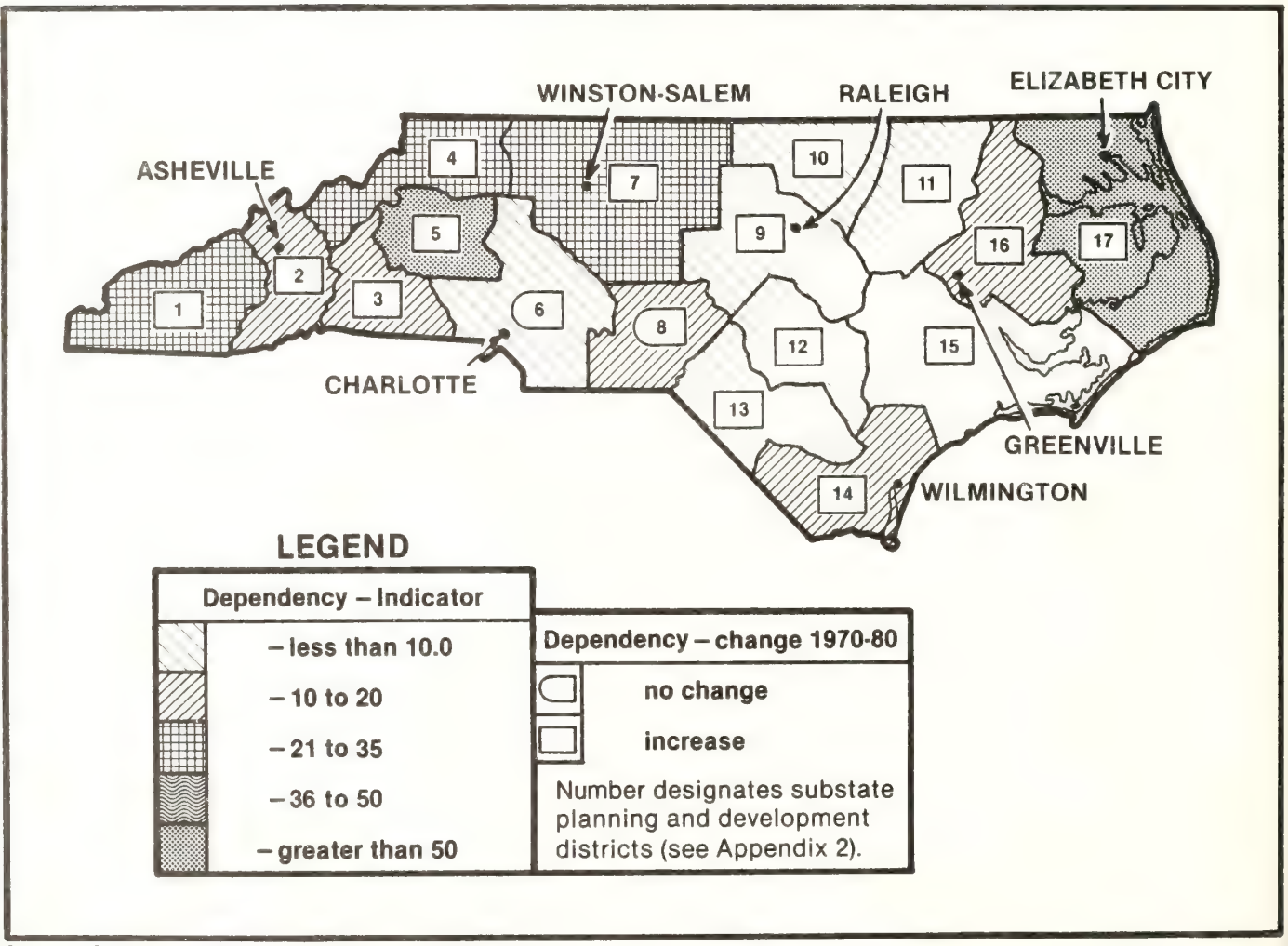
In 1980, ten industries accounted for 99 percent of the State's excess employment—that is, its economic base (see tabulation below). Though these same industries accounted for approximately the same share in 1970, the change in shares of certain individual industries is noteworthy. Agriculture, for example, was less important in 1980 than in 1970. The forest products industry gained in importance between 1970 and 1980. Meanwhile, the State's most important basic industry—textile and apparel—experienced a slight gain in importance.

Economic base industries	Dependency indicator	
	1970	1980
	(Percent of economic base)	
Textiles and apparel	53.35	53.73
Forest products[1/]	11.71	16.34
Agriculture	18.13	10.36
Federal military	9.55	9.24
Tobacco	4.84	4.56
Trucking and warehousing	1.26	1.82
Chemical and allied products	—	1.72
Rubber and miscellaneous plastics	—	.77
Other furniture and fixtures	—	.37
Mobile homes	.14	.35
Subtotal	98.98	99.26
All other basic industries	1.02	.74
Total	100.00	100.00

[1/]The forest products industry is comprised of (1) lumber and wood products (SIC 24), except mobile homes (SIC 2451); and (2) wood furniture manufacturing (SIC 2511, 2512, 2517, 2521, and 2541), and paper and allied products (SIC 26).

Geographical Importance of the State's Forest Products Industry

The contribution of the forest products industry to North Carolina's economic base varies considerably between substate districts (see Appendix 2 for a listing of counties by district). Generally speaking, the forest products industry is less important in the central part of the State than elsewhere. For example, the forest products industry accounts for at least 20 percent of the economic base (that is, those industries producing for export to areas outside the district, or State, and the rest of the world) in the western third of the State, but less than 10 percent in the Raleigh area. Furthermore, the forest products industry accounts for more than 50 percent of the economic base of the State's northern coastal zone. North Carolina's dependency on the forest products industry to produce exports increased in most substate districts between 1970 and 1980. The exception was in the central part of the State, where the dependency on the forest products industry did not change.

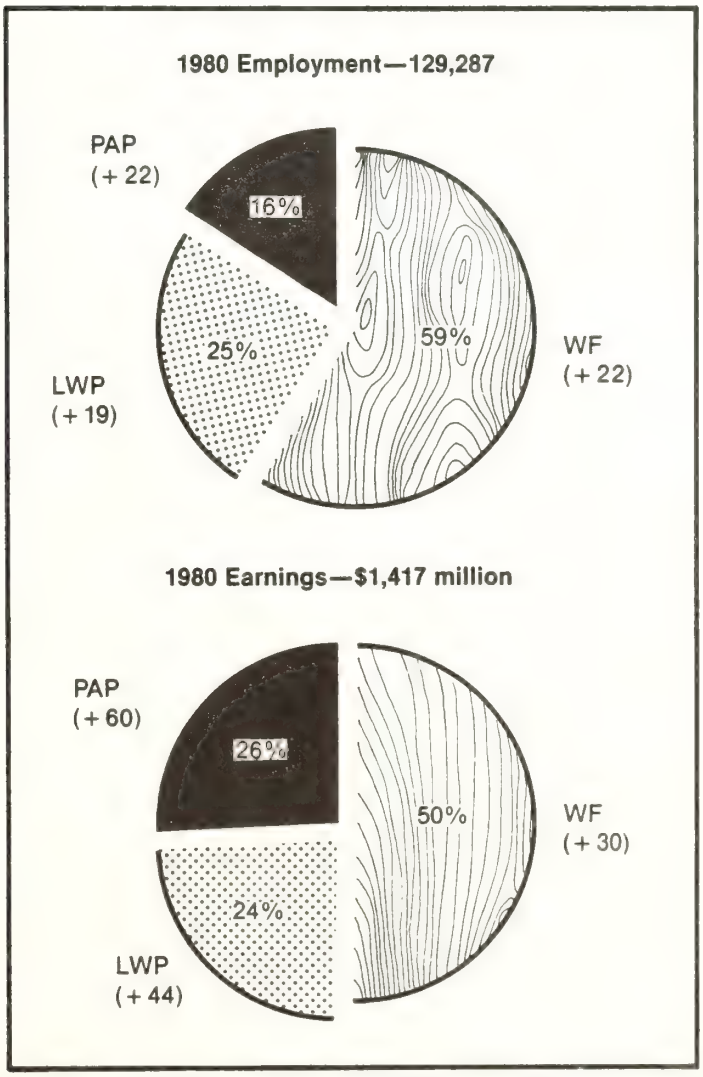


Source: Substate estimates for 1970 and 1980 were derived from unpublished county data series provided by the U.S. Department of Commerce, Regional Economic Information System, Washington, DC; and from the Department's *County Business Patterns*. The numbers in the squares and circles used to designate substate districts correspond to the geographical classification of counties as shown in Appendix 2.

Composition of the State's Forest Products Industry

North Carolina's forest products industry is comprised of paper and allied products, lumber and wood products (not including mobile homes), and wood furniture manufacturing. In 1980, wood furniture manufacturing accounted for the largest share of approximately 129,000 workers employed by North Carolina's forest products industry. It also had the largest share of 1980 earnings. North Carolina accounted for 26 percent of the Nation's wood furniture manufacturing employees and 24 percent of the earnings.

During the 1970's, employment in all segments of the State's forest products industry increased. Growth in FPI employment, however, was slower than the average for all industries in the Nation (22.3 percent). But earnings for all three segments exceeded the national average (27.4 percent). Growth of wood furniture earnings lagged behind those in paper and allied products and in lumber and wood products.

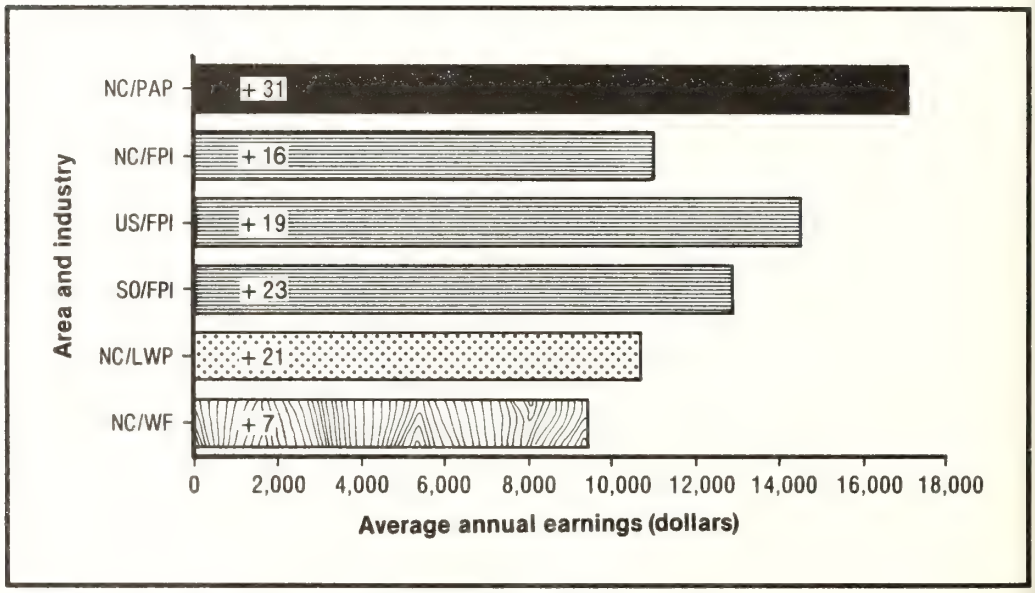


Numbers in parentheses show percentage of change from 1970 to 1980.

Average Annual Earnings per Worker

Average annual 1980 earnings per worker in paper and allied products were significantly greater than were earnings in the other two components. Higher average skill levels, capital investment per worker, and unions account for this difference. Earnings in the wood furniture component were nearly half those in paper and allied products and significantly below the average in all forest products industries in the South and the United States.

Average annual earnings in North Carolina's forest products industry were significantly less than the average for the forest products industry in the South or in the rest of the Nation. Moreover, growth in earnings was less for North Carolina than for the South and the Nation. Growth and the level of earnings for wood furniture were considerably less than for the rest of the forest products industry in North Carolina, the South, and the United States.

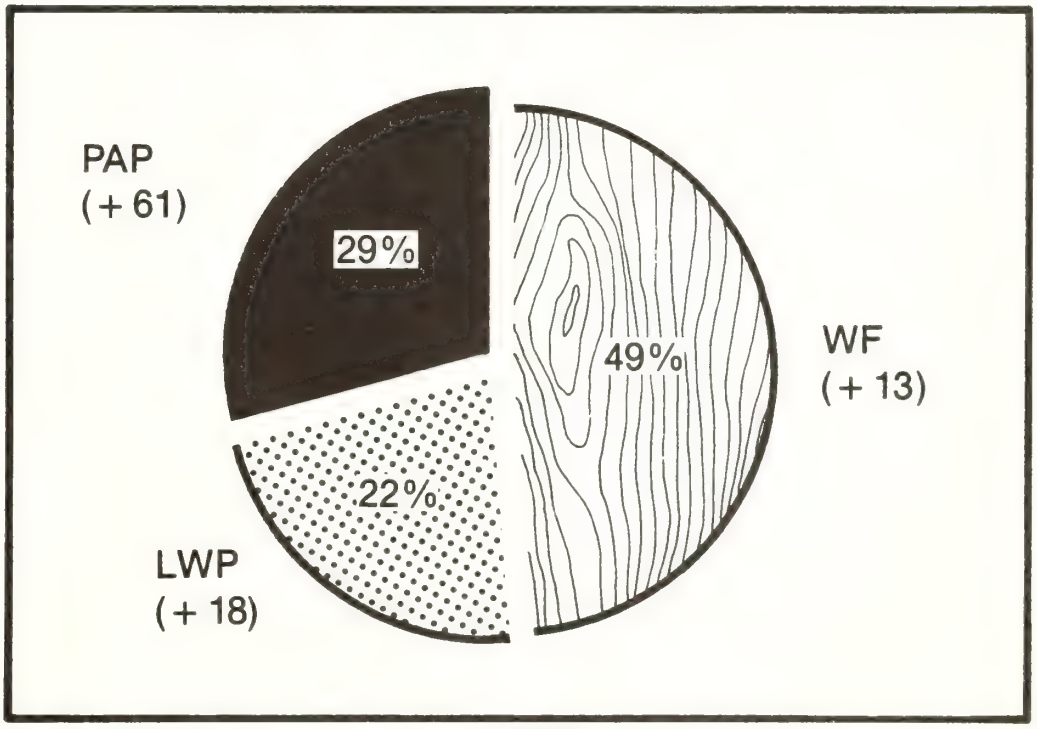


Numbers in bars show percentage of change from 1970 to 1980.

Value Added by the Forest Products Industry

Value added by manufacturing represents income payments directly to workers and business owners. It is equal to the value of shipments less the cost of materials, parts, supplies, fuel, goods purchased for resale, electric energy, and contract work. Unlike value of shipments, value added avoids double counting. Consequently, value added by manufacturing is considered the best monetary gauge of the relative economic importance of a manufacturing industry.

In 1977, wood furniture accounted for nearly half of the $2.4 billion of the value added by North Carolina's forest products industry. But between 1972 and 1977, the value added by paper and allied products grew nearly five times as fast as that of wood furniture.

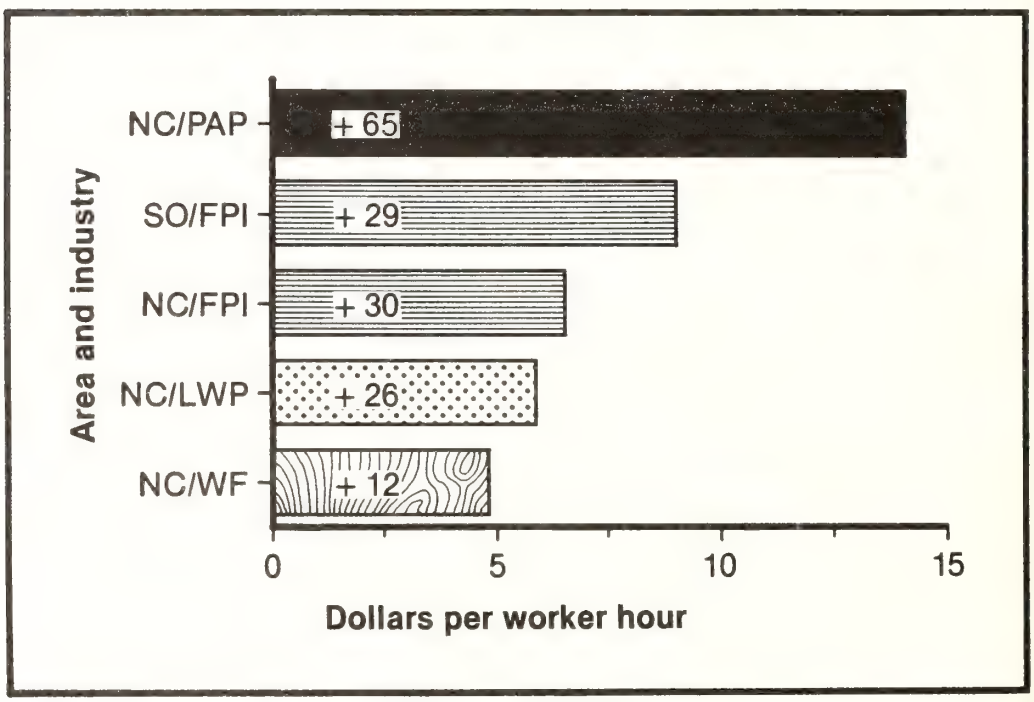


Numbers in parentheses show percentage of change from 1972 to 1977.

Capital Productivity

Increases in productivity are necessary for an industry to remain competitive in the marketplace. Capital productivity of an industry is measured in terms of value added minus payroll—VAMP (see table 3 for an explanation of how capital productivity was calculated for North Carolina's forest products industry). This measure of productivity adjusts for wide differences in payroll among industries and represents the return to capital investment and entrepreneurship.

Not surprisingly, paper and allied products had the highest productivity in North Carolina's forest products industry. This component is more capital intensive and in the past has attracted considerable investment in new facilities and equipment. Furthermore, during the mid-1970's, it exhibited a larger gain in productivity than either the lumber and wood products or wood furniture. The relatively low productivity of wood furniture as compared to the rest of the forest products industry reflects the labor-intensive nature of its manufacturing process.

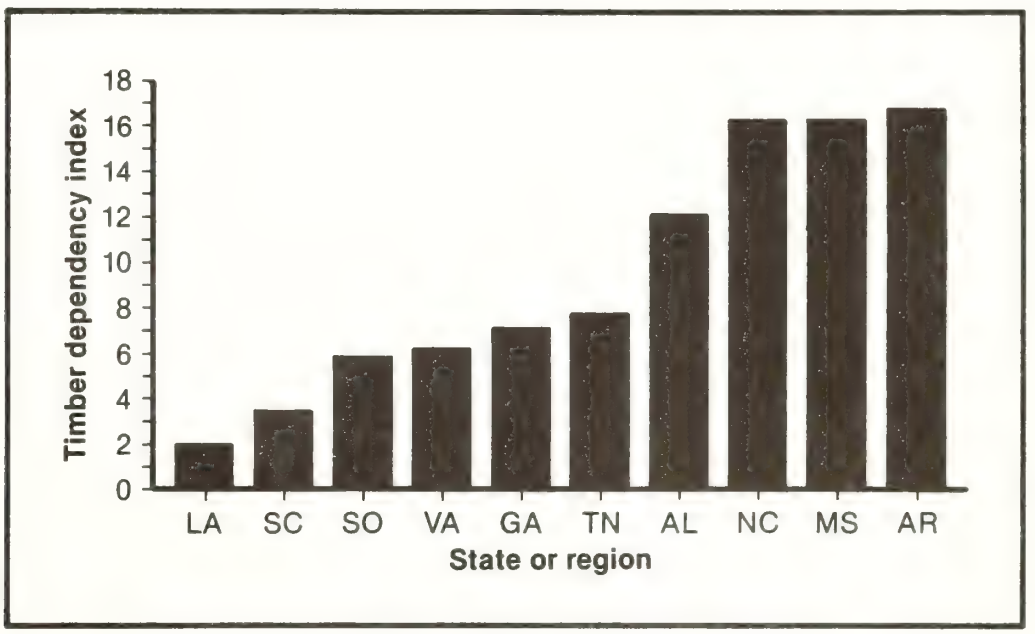


Numbers in bars show percentage of change from 1972 to 1977.

The Forest Products Industry in the South

Importance of the Industry Across the South

The dependency indicators suggest that, in 1980, all but four States in the South manufactured forest products in excess of State-wide needs. Florida, Kentucky, Oklahoma, and Texas were not self-sufficient with respect to forest products. That is, these States imported more forest products, in terms of value, than they exported. Consequently, on net balance, their respective forest products industries did not generate new dollars from outside. In North Carolina, the forest products industry accounted for 16.3 percent of economic base employment, or approximately 1 out of 6 basic employees. In two other States—Arkansas and Mississippi—the forest products industry also accounted for approximately 16 percent of the basic employment.



Industry Composition

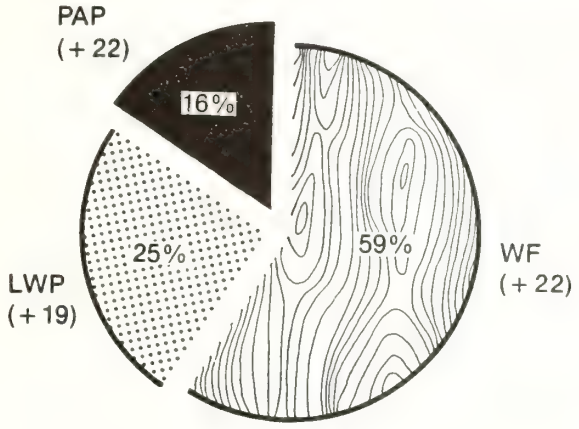
In 1980, North Carolina had more forest products industry employees than did any other Southern State. It had approximately 21 percent of the South's forest products industry employment and 18 percent of total earnings.

Wood furniture manufacturing accounted for a much larger share of North Carolina's 1980 forest products industry employment and earnings than it did for either the South or the Nation. Wood furniture employment increased much faster in North Carolina between 1970 and 1980 than in either the South or the Nation. The growth of wood furniture earnings in North Carolina greatly exceeded the rate for the South and Nation.

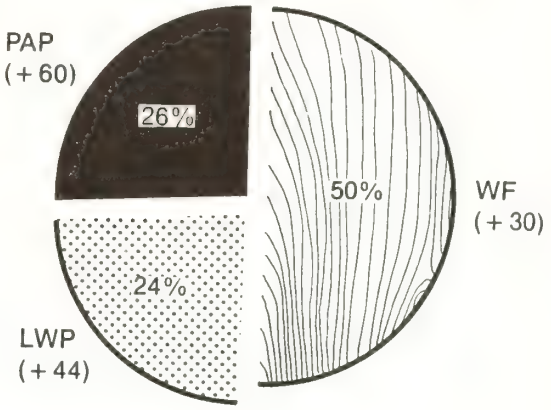
Paper and allied products is a less important segment of the forest products industry in North Carolina than in the South or the Nation. But its growth of employment and earnings was greater for North Carolina than for either the South or the United States. Lumber and wood products also experienced significantly greater growth of employment and earnings during the 1970's than did its counterparts in the South and the Nation.

NORTH CAROLINA

1980 Employment—129,287

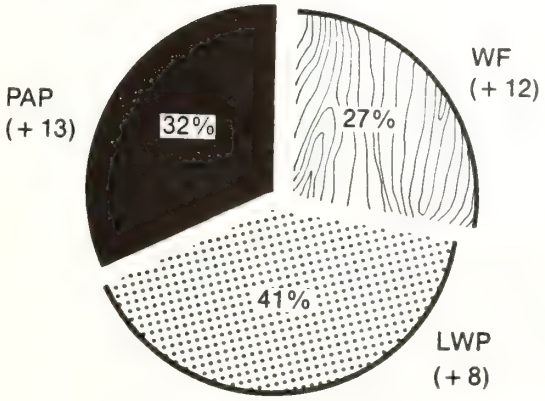


1980 Earnings—$1,417 million

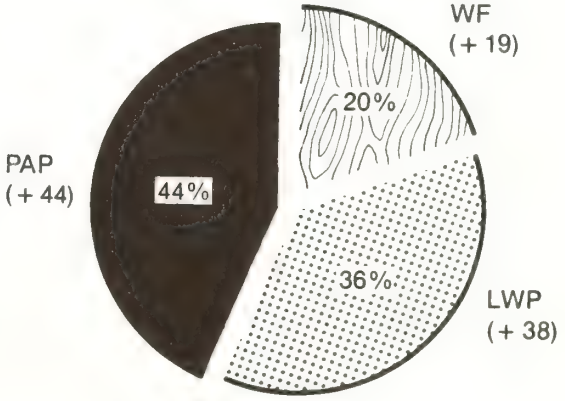


THE SOUTH

1980 Employment—620,567

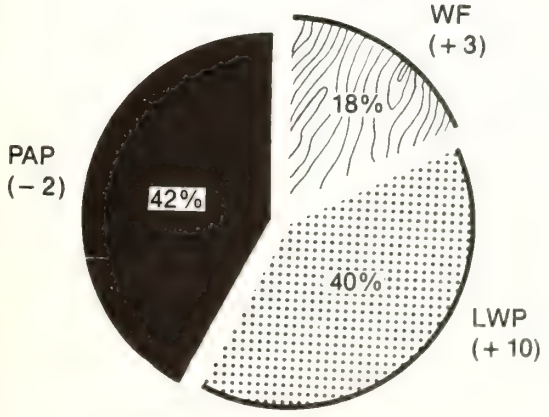


1980 Earnings—$7.96 billion

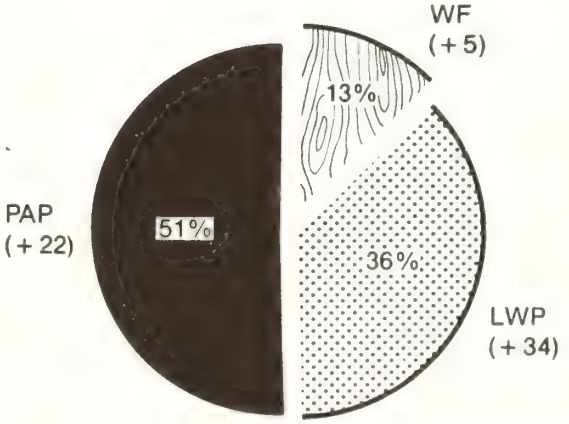


UNITED STATES

1980 Employment—1,634,000



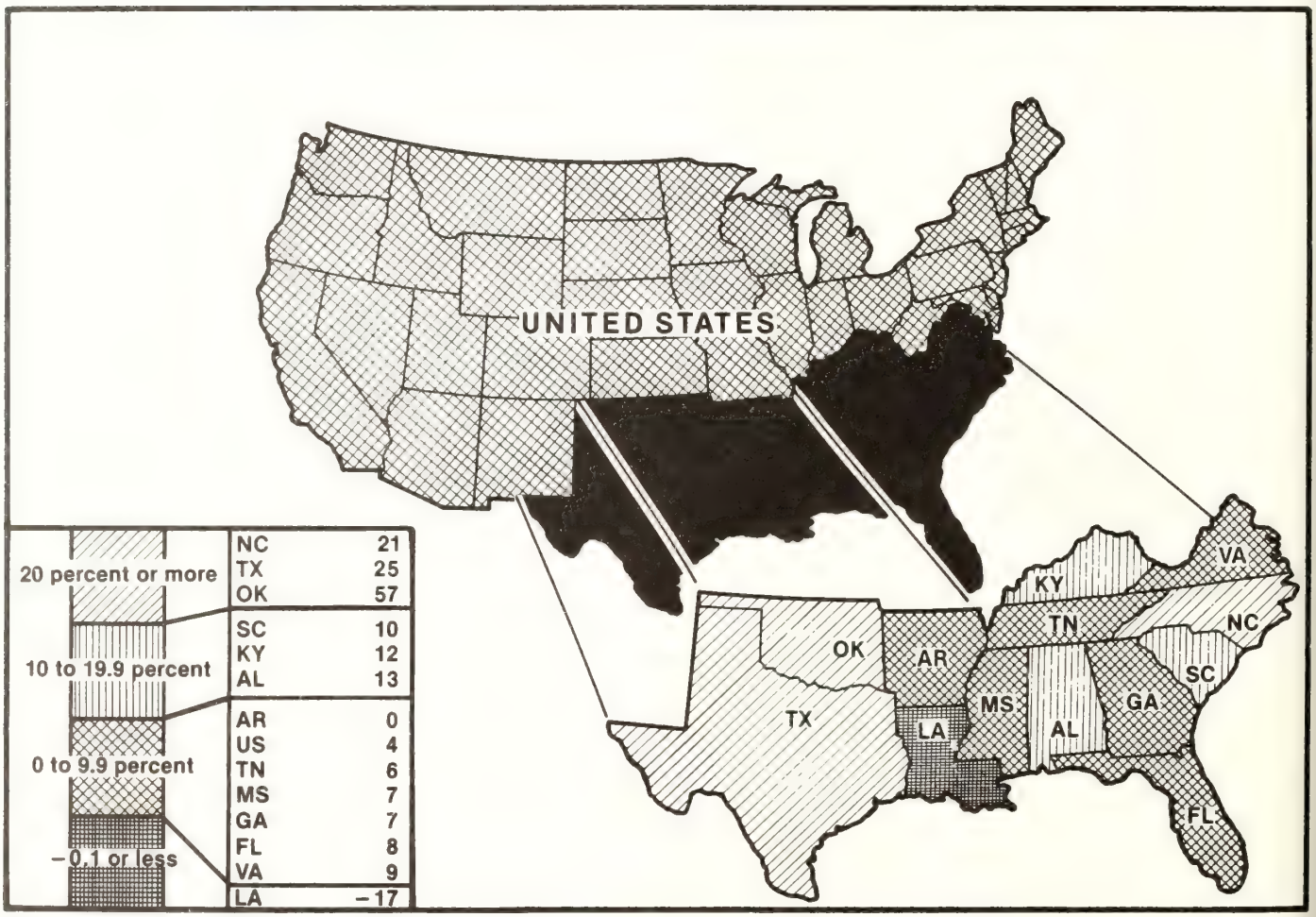
1980 Earnings—$23.65 billion



Numbers in parentheses show percentage of change from 1970 to 1980. Earnings are expressed in constant 1977 dollars.

Growth of Employment

With the exception of Arkansas and Louisana, forest products industry employment in each of the Southern States grew faster from 1970 to 1980 than did the U.S. counterpart. Employment in two States—Oklahoma and Texas—grew faster than the all-industry average of 22.3 percent. Employment growth in North Carolina's forest products industry was approximately five times the national rate and ranked third among the 13 Southern States.

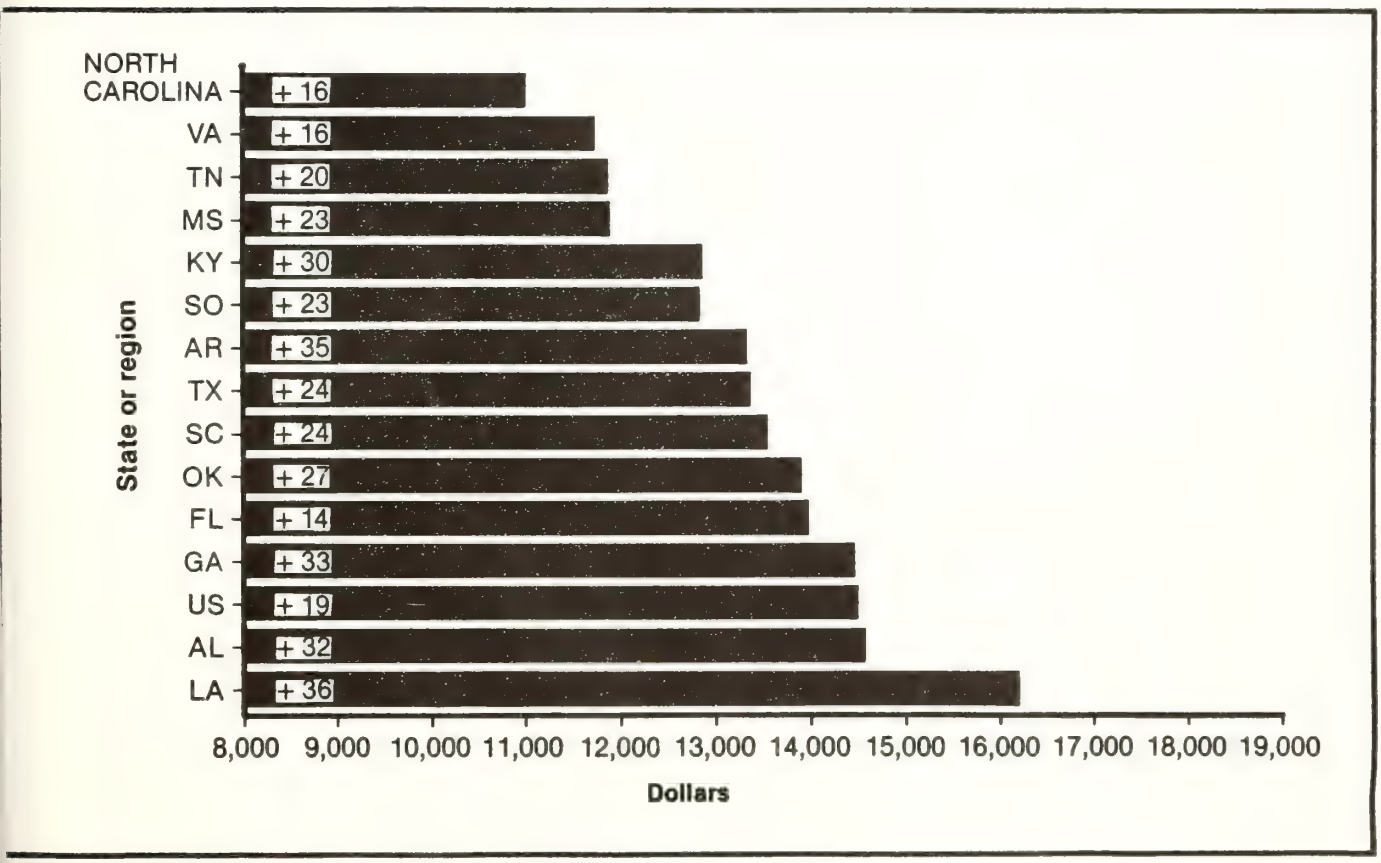


Average Annual Earnings

Average annual earnings per worker in the forest products industry differed significantly by State in 1980. Approximately $5,000 separated the State with the highest—Louisiana—from the State with the lowest—North Carolina. Pulp and allied products manufacturing, which has traditionally paid higher wages than have other segments of the forest products industry, dominated Louisiana's forest products industry. Wood furniture, which has paid lower average wages, dominated North Carolina's forest products industry.

Average annual earnings per worker in North Carolina's forest products industry were nearly one-fourth less than the industry's U.S. average. North Carolina ranked last in the South in average annual earnings per worker, and only Florida experienced slower growth in earnings during the 1970's.

Generally speaking, paper and allied products dominated the forest products industry in the States with the highest average annual earnings. This relationship reflects higher job skills and unions in pulp and paper manufacturing. Wages, by and large, were the lowest in those States where labor-intensive wood furniture manufacturing was more important.



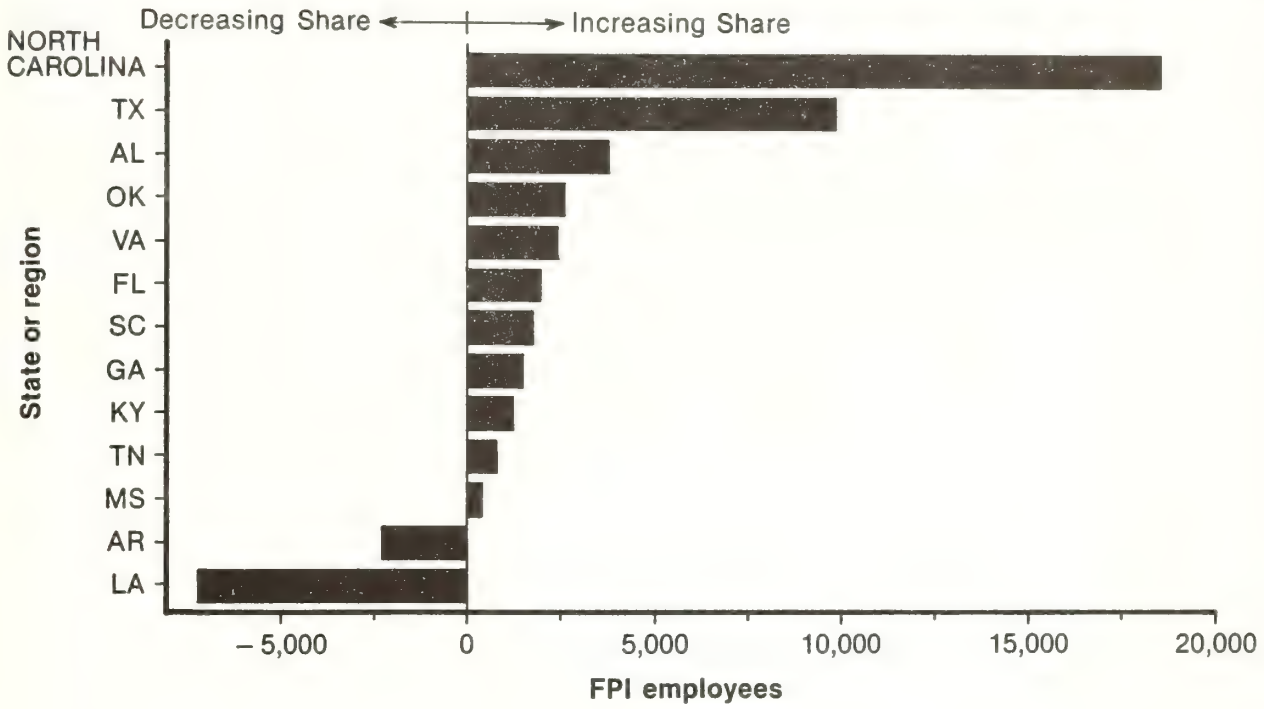
Numbers in bars show percentage of change from 1970 to 1980.

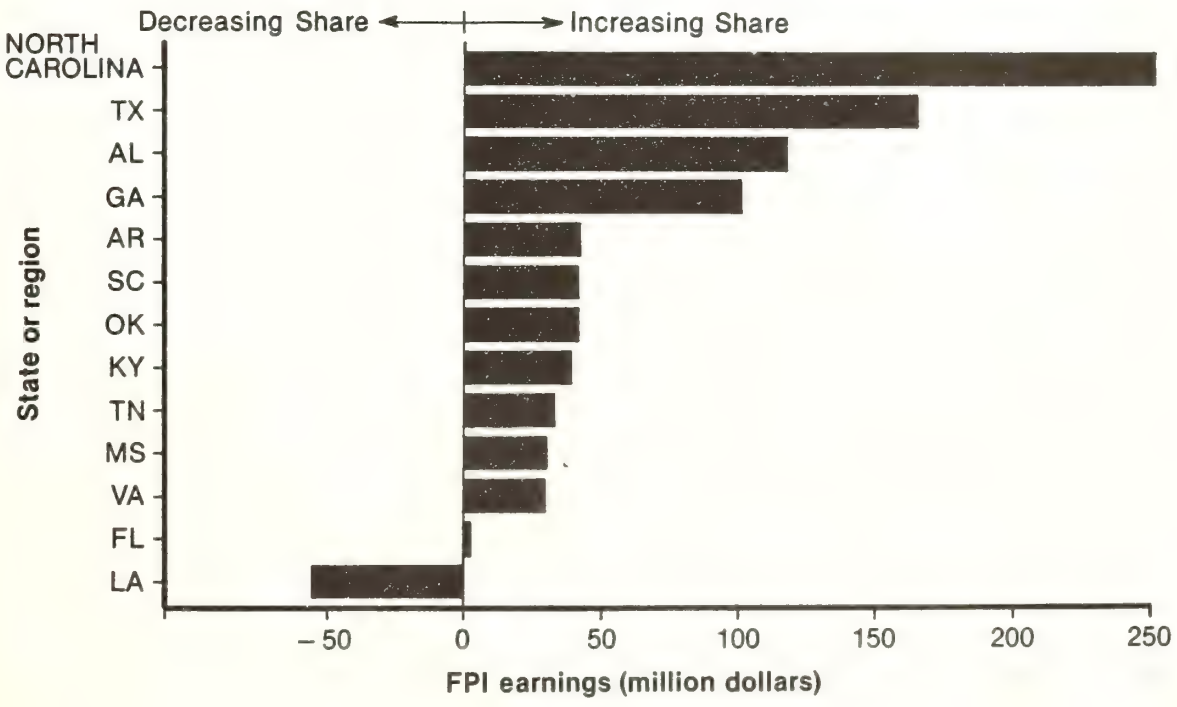
Shift in Employment and Earnings

The regional shift shows how much more or less employment and earnings a State would have had in the forest products industry in 1980 had it grown at the national rate. For example, North Carolina had approximately 19,500 more employees in 1980 than it would have had if its forest products industry had grown at the national rate.

Between 1970 and 1980, employment in the forest products industry increased in every Southern State except Louisiana and Arkansas. Moreover, all but these two States increased their share of the Nation's forest products industry employment, and all but Louisiana increased their share of earnings. North Carolina experienced the largest gain in both employment and earnings of any other Southern State.

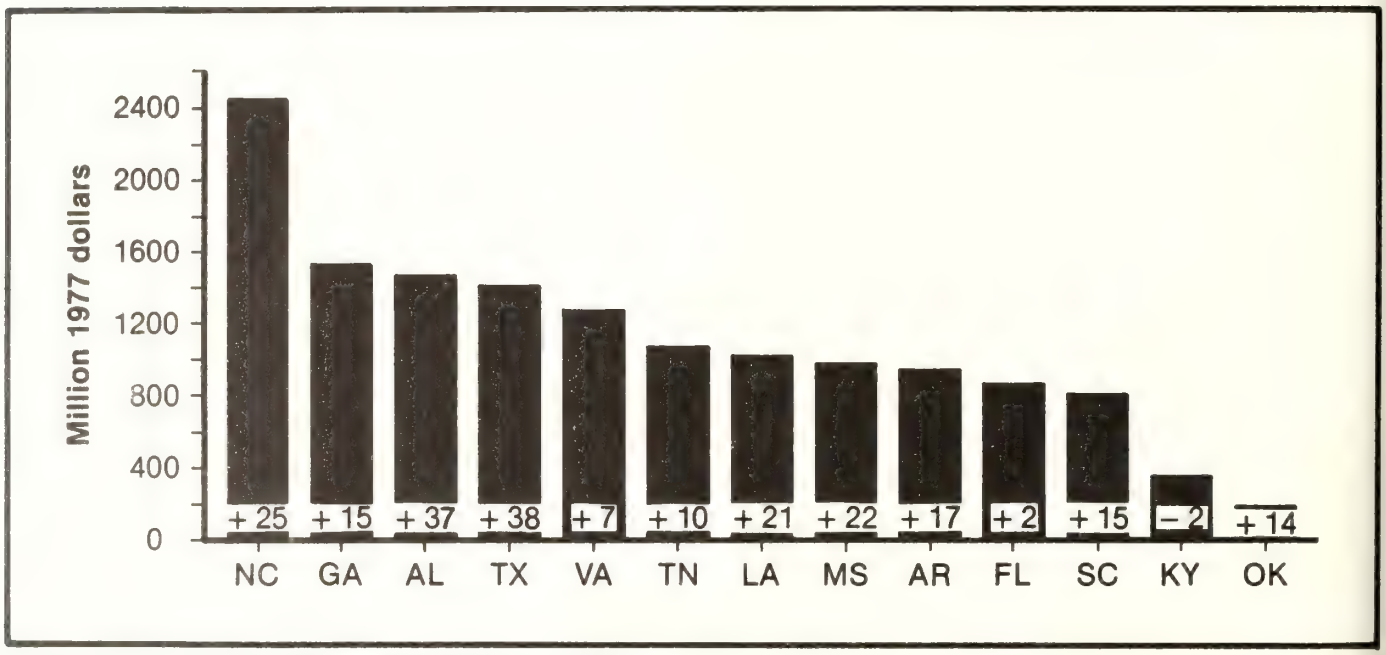
Increased shares of employment and earnings reflect the comparative advantage the South's forest products industry enjoyed over this industry in the rest of the Nation. Several factors (for example, relatively lower labor costs, lower raw materials costs, and closer proximity to markets) might account for a region's comparative advantage, although adverse trends with respect to one factor need not reduce a region's advantage. In the case of the South, for instance, increasing labor costs need not adversely affect its comparative advantage if increased capital or labor productivity offsets higher labor costs.


Decreasing Share
Increasing Share
NORTH CAROLINA
TX
AL
OK
VA
FL
SC
GA
KY
TN
MS
AR
LA
State or region
– 5,000
0
5,000
10,000
15,000
20,000
FPI employees


Decreasing Share
Increasing Share
NORTH CAROLINA
TX
AL
GA
AR
SC
OK
KY
TN
MS
VA
FL
LA
State or region
– 50
0
50
100
150
200
250
FPI earnings (million dollars)

Value Added by the Forest Products Industry

In 1977, the forest products industry of North Carolina produced more value added than any other State in the South. Georgia was second among the 13 Southern States, followed by Alabama. Texas was not only one of the leading States in terms of total value added, it also led the South in terms of the change in value added between 1972 and 1977. One State, Kentucky, produced less value added in 1977 than in 1972.

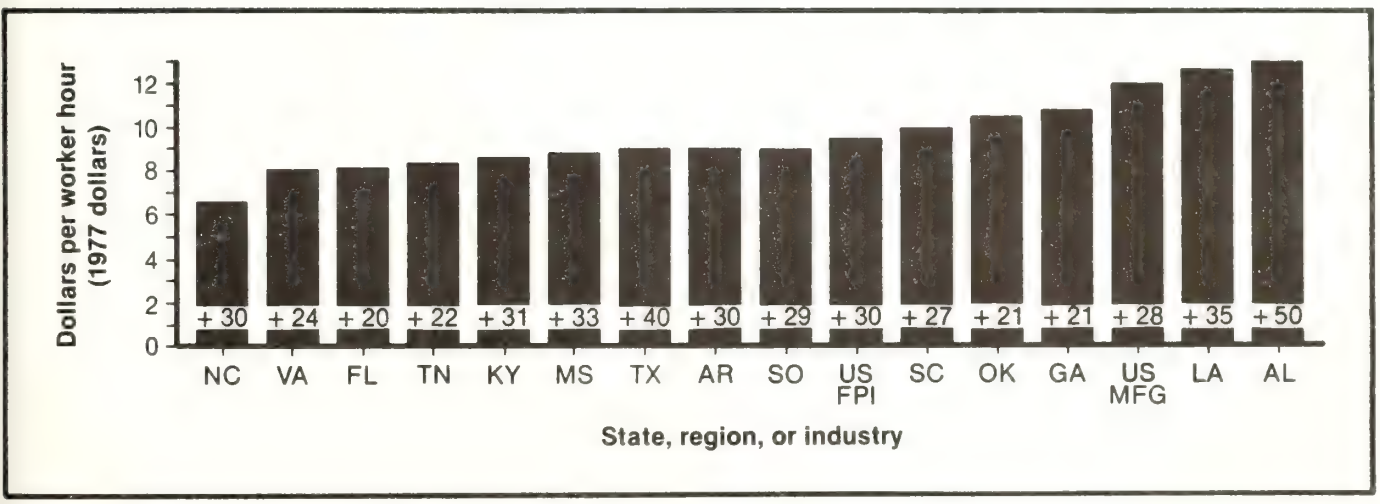


Numbers in bars show percentage of change from 1972 to 1977.

Capital Productivity

Paper and allied products, which is more capital-intensive and, therefore, more susceptible to technological change than other segments of the forest products industry, exhibited the highest productivity within the forest products industry. Wood furniture, on the other hand, is the most labor-intensive of the three. North Carolina, for example, produced more value added than any other State in the South, but the productivity of its forest products industry in 1977 was the lowest. This reflects the dominant role of labor-intensive wood furniture manufacturing in North Carolina.

Increases in productivity exceeded increases in payroll per worker between 1972 and 1977 for all the Southern States. This relationship is in part responsible for the South's comparative advantage in the forest products industry. The average productivity for all-manufacturing industries in the Nation exceeded that of the forest products industries in 11 of the 13 Southern States. But the forest products industries in five Southern States exceeded the average productivity for the Nation. Furthermore, the increase in productivity of North Carolina's forest products industry, and that of six other Southern States, exceeded the increase for all of the Nation's manufacturing industries.



Numbers in bars show percentage of change from 1972 to 1977.

Acknowledgment

Many helpful suggestions of several reviewers were incorporated in this research paper. This project was partially funded by the USDA Forest Service, Resource Program and Assessment Staff, State and Private Forestry, Area Planning and Development, State Planning for Forest Resources.

Appendix 1
Tables

Table 1—Total labor and proprietorial employment and income, by industry, North Carolina, 1980[1/]

Industry number	Industry	Employees	Total Income
		Number	*Thousand 1977 dollars[2/]*
Wage and salary			
1	Agriculture	55,297	993,243
2	Agricultural services, forestry, and fisheries	13,159	105,285
3	Coal mining	0	3,062
4	Oil and gas extraction	26	693
5	Metal mining	42	184
6	Nonmetallic minerals	5,097	730,44
7	Construction	119,469	1,459,677
8	Food and kindred products	44,975	507,442
9	Tobacco	25,485	488,822
10	Textile mill production	248,244	2,370,802
11	Apparel and other textiles	88,153	625,319
12	Paper and allied products[3/]	21,397	364,447
13	Printing and publishing	20,634	221,474
14	Chemical and allied products	39,289	606,709
15	Petroleum refining	692	11,229
16	Rubber and miscellaneous plastics	23,853	308,842
17	Leather and leather products	5,060	43,453
18	Lumber and wood products, except mobile homes[3/]	31,933	339,980
19	Mobile homes	3,096	32,962
20	Wood furniture[3/]	75,957	712,675
21	Other furniture and fixtures	6,602	61,944
22	Stone, clay, and glass products	18,069	230,215
23	Primary metals	8,508	134,459
24	Fabricated metals	27,340	368,611
25	Machinery, excluding electrical	48,624	723,820
26	Electrical machinery	55,990	774,795
27	Transportation equipment except motor vehicles	3,279	42,311
28	Motor vehicles	11,444	172,036
29	Ordnance	[4/]	[4/]
30	Instruments and related equipment	10,029	143,558
31	Miscellaneous manufacturing	6,474	64,116
32	Railroad transportation	7,104	144,026
33	Trucking and warehousing	44,366	684,908
34	Local transit	3,690	42,578
35	Air transportation	5,920	104,577
36	Pipeline transportation	114	2,449

See footnotes at end of table.

Table 1—Total labor and proprietorial employment and income, by industry, North Carolina, 1980[1/] (continued)

Industry number	Industry	Employees	Total Income
		Number	*Million 1977 dollars[2/]*
Wage and salary			
37	Transportation services	1,485	24,245
38	Water transportation	2,204	18,070
39	Communications	29,217	504,578
40	Electrical, gas, and sanitation services	23,428	412,246
41	Wholesale trade	122,102	1,716,764
42	Retail trade	352,315	2,679,193
43	Banking	29,948	328,014
44	Other credit agencies	16,844	229,112
45	Insurance	32,331	474,798
46	Real estate and combinations	17,553	218,837
47	Hotel and other lodging	19,028	121,588
48	Personal, miscellaneous business, and repair services	77,963	774,941
49	Auto repair service	11,794	163,082
50	Amusement	11,217	73,668
51	Motion pictures	3,082	17,201
52	Private households	66,725	172,421
53	Medical and other health	83,050	1,172,294
54	Private education	33,612	314,791
55	Nonprofit organizations	62,835	388,984
56	Miscellaneous services	26,447	606,727
57	Federal civilian	49,804	706,334
58	Federal military	114,704	885,868
59	State and local government	355,613	3,238,818
Proprietorial			
60	Farm proprietors	110,361	770,234
61	Nonfarm proprietors	181,899	1,742,059
	Total	2,914,972	30,718,614

[1/] Source of data for this table for North Carolina, other States of the South, and the United States: unpublished data, U.S. Department of Commerce, Regional Economics Measurements Division, Regional Economic Information System (REIS), Washington, DC, 1982. Unpublished data used by the U.S. Department of Commerce in preparing their *County Business Patterns* (CBP) series on employment and payroll were used to differentiate wood-related from nonwood-related employment and earnings. For example, CBP data were used to separate mobile homes (no. 19, above) from the lumber and wood products (no. 18) industry. Wood furniture (no. 20) was similarly separated from other furniture and fixtures (no. 21).

[2/] The Personal Consumption Expenditures (CPE) deflator, 1977 = 100, was used to deflate actual dollars.

[3/] The forest products industry is comprised of (1) lumber and wood products (SIC 24), except mobile homes (SIC 2451); and (2) wood furniture manufacturing (SIC 2511, 2512, 2517, 2521, and 2541), and paper and allied products (SIC 26).

[4/] Included with fabricated metals and other related industries.

Table 2—Calculation of 1980 dependency indexes for North Carolina
(In percent)

Industry	Employment		North Carolina excess employment[1/]	Dependency index[2/]
	North Carolina	United States		
Agriculture	2.22	1.46	.76	3.64
Agricultural services, forestry, and fisheries	.53	.62		
Farm proprietors	4.43	3.03	1.40	6.72
Coal mining	0	.27		
Oil and gas extraction	0	.60		
Metal mining	0	.11		
Nonmetallic minerals	.20	.14	.07	.33
Construction	4.79	4.74	.05	.24
Food and kindred products	1.80	1.87		
Tobacco	1.02	.07	.95	4.56
Textile mill production	9.96	.93	9.03	43.40
Apparel and other textiles	3.54	1.39	2.15	10.33
Paper and allied products	.86	.76	.10	.49
Printing and publishing	.83	1.37		
Chemical and allied products	1.58	1.22	.36	1.72
Petroleum refining	.03	.22		
Rubber and miscellaneous plastics	.96	.80	.16	.77
Leather and leather products	.20	.26		
Lumber and wood products, except mobile homes	1.28	.71	.57	2.75
Mobile homes	.12	.05	.07	.35
Wood furniture	3.05	.32	2.72	13.10
Other furniture and fixtures	.26	.19	.08	.37
Stone, clay, and glass products	.72	.73		
Primary metals	.34	1.26		
Fabricated metals	1.10	1.77		
Machinery, excluding electrical	1.95	2.73		
Electrical machinery	2.25	2.31		
Transportation equipment except motor vehicles	.13	1.21		
Motor vehicles	.46	.87		
Ordnance	0	0		
Instruments and related equipment	.40	.77		
Miscellaneous manufacturing	.26	.47		
Railroad transportation	.28	.58		
Trucking and warehousing	1.78	1.40	.38	1.82
Local transit	.15	.29		
Air transportation	.24	.50		
Pipeline transportation	0	.02		
Transportation services	.06	.22		
Water transportation	.09	.23		
Communications	1.17	1.48		
Electrical, gas, and sanitation services	.94	.90	.04	.18
Wholesale trade	4.90	5.79		
Retail trade	14.13	16.50		
Banking	1.20	1.72		

See footnotes at end of table.

Table 2—Calculation of 1980 dependency indexes for North Carolina (continued)

(In percent)

Industry	Employment		North Carolina excess employment[1/]	Dependency index[2/]
	North Carolina	United States		
Other credit agencies	.68	.99		
Insurance	1.30	1.89		
Real estate and combinations	.70	1.16		
Hotel and other lodging	.76	1.20		
Personal, miscellaneous business, and repair services	3.13	4.69		
Auto repair service	.47	.63		
Amusement	.45	.84		
Motion pictures	.12	.24		
Medical and other	3.33	5.71		
Private education	1.35	1.47		
Nonprofit organizations	2.52	3.01		
Miscellaneous services	1.06	1.63		
Federal civilian	2.00	3.27		
Federal military	4.60	2.68	1.92	9.24
Nonfarm proprietors	7.30	7.66		
Total[3/]	100.00	100.00	20.80	100.00

[1/] U.S. employment minus North Carolina employment. Figures may not be exactly equal to North Carolina minus U.S. because of rounding. Dashes signify no excess employment.

[2/] Individual industry excess employment expressed as a percentage of North Carolina's total excess employment (sum of column 4).

[3/] Sum of parts may not equal totals because of rounding.

Table 3—Value added, hours worked, payroll, and capital productivity, [1/] North Carolina forest products industry, 1977[2/]

Industry	Value added	Payroll	Hours worked	Productivity	Productivity change, 1972-77
	- - $Million - -		*Million*	*$VAMP per hour*	*Percent*
Lumber and wood products	539.3	228.6	48.8	5.87	26.39
Wood furniture	1,193.4	598.9	123.7	4.80	12.14
Paper and allied products	715.7	267.0	31.9	14.06	64.82

[1/] Productivity equals value added minus payroll (VAMP), divided by hours worked. For a discussion of VAMP, see W. Charles Sawyer and Joseph A. Ziegler. 1980. The use of VAMP shift as a predictive model. Unpublished paper presented at the annual meeting of the Western Regional Science Association, Monterey, California.

[2/] Source: U.S. Bureau of the Census, Census of Manufacturing, for 1972 and 1977, North Carolina and the United States, available in 1976 and 1980, respectively. In the few instances where data were not available for some subindustry components, the distribution of the number of establishments was used to estimate nondisclosures.

Appendix 2
North Carolina Counties by Substate Planning and Development Districts

District code	Counties
1	Cherokee, Clay, Graham, Haywood, Jackson, Macon, and Swain
2	Buncombe, Henderson, Madison, and Transylvania
3	Cleveland, McDowell, Polk, and Rutherford
4	Alleghany, Ashe, Avery, Mitchell, Watauga, Wilkes, and Yancey
5	Alexander, Burke, Caldwell, and Catawba
6	Cabarrus, Gaston, Iredell, Lincoln, Mecklenburg, Rowan, Stanly, and Union
7	Alamance, Caswell, Davidson, Davie, Forsyth, Guilford, Randolph, Rockingham, Stokes, Surry, and Yadkin
8	Anson, Montgomery, Moore, and Richmond
9	Chatham, Durham, Johnston, Lee, Orange, and Wake
10	Franklin, Granville, Person, Vance, and Warren
11	Edgecombe, Halifax, Nash, Northampton, and Wilson
12	Cumberland, Harnett, and Sampson
13	Bladen, Hoke, Robeson, and Scotland
14	Brunswick, Columbus, New Hanover, and Pender
15	Carteret, Craven, Duplin, Greene, Jones, Lenoir, Onslow, Pamlico, and Wayne
16	Beaufort, Bertie, Hertford, Martin, and Pitt
17	Camden, Chowan, Currituck, Dare, Gates, Hyde, Pasquotank, Perquimans, Tyrrell, and Washington.

Schallau, Con H; Maki, Wilbur R.; Foster, Bennett B.; Redmond, Clair H. North Carolina's forest products industry: performance and contribution to the State's economy, 1970 to 1980. Res. Pap. PNW-343. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 22 p.

Employment and earnings in North Carolina's forest products industry, like those of most Southern States, grew significantly between 1970 and 1980. The forest products industry accounted for a larger share of the State's economic base in 1980 than in 1970. North Carolina had more forest products industry employment than any other State in the South. Moreover, during this period, the State increased its share of the Nation's forest products industry employment and earnings. Pulp and allied products had the highest productivity in 1977 and the largest increase in productivity between 1972 and 1977.

Keywords: Forest products industries, economics (forest products industries), North Carolina.

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Research Paper
PNW-344
October 1985

Growth Response of Suppressed True Fir and Mountain Hemlock After Release

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Abstract

Seidel, K. W. Growth response of suppressed true fir and mountain hemlock after release. Res. Pap. PNW-344. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 22 p.

The diameter and height growth of advance reproduction of suppressed true fir (*Abies* spp.) and mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) was measured in south-central Oregon after release by overstory removal in clearcuttings, shelterwood units, and uncut stands. Postrelease growth was greatest in clearcuttings, intermediate in shelterwood cuttings, and slowest in uncut stands. Multiple regression analyses were used to predict growth response as a function of tree and stand variables. Overstory basal area, live crown ratio, and past 5-year height growth accounted for the most variation in diameter and height growth after release. Vigorous advance reproduction having live crown ratios greater than 50 percent are the best candidates for crop trees.

Keywords: Growth response, release, suppression (tree), advance growth, true fir, mountain hemlock.

Summary

In 1983 and 1984, a study was conducted in the Cascade Range in south-central Oregon to obtain information about the diameter and height growth response of suppressed advance reproduction of grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), Shasta red fir (*Abies magnifica* var. *shastensis* Lemm.), and mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) after release by removal of the overstory. The purpose was to compare rates of diameter and height growth before and after release, to determine when increased growth occurs, and to develop models to predict diameter and height growth after release as a function of tree and stand variables, such as live crown ratio and basal area.

The study areas were clearcut and shelterwood units and uncut stands in upper slope, mixed conifer/snowbrush-chinkapin and mountain hemlock/grouse huckleberry communities in the Deschutes and Winema National Forests, south-central Oregon. Growth patterns 5 years before and 10 to 20 years after release of the trees were determined by sectioning trees.

Both diameter and height growth increased after release from two to four times the prerelease rate for both fir and hemlock. Acceleration of growth generally occurred within 5 years after release with the most rapid growth occurring on clearcut units. Growth curves had a sigmoid form showing constant growth before release, a rapid acceleration during the first 8 to 9 years after release, followed by a flattening of the curves from 10 to 20 years after release.

Residual overstory basal area, live crown ratio, and past 5-year height growth were the three variables accounting for most of the variation in diameter and height growth after release. Growth of the advance reproduction after release was directly proportional to live crown ratio or past height growth and inversely proportional to overstory stand density. Both fir and hemlock responded to release regardless of age.

The best potential crop trees are vigorous advance reproduction having live crown ratios greater than 50 percent and those with the greatest height growth before release. Releasing these trees by removing the overstory and by thinning when needed will not only greatly increase growth rates but will afford some protection against heartrots.

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Introduction

A suppressed understory consisting of shade-tolerant species such as true firs (*Abies* spp.) and mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) is present in many mixed conifer communities on the east slopes of the Cascade Range in central Oregon. Using this advance reproduction for the new stand after removing the existing overstory, instead of relying on natural or artificial regeneration, has advantages in many situations. One of the key factors in evaluating the potential of suppressed advance reproduction is the growth response of the trees after release. Of interest are whether trees will respond with increased diameter and height growth and, if so, the magnitude and timing of the response.

Many studies show that understories of true fir and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) will respond to release even though suppressed for many years (Crossley 1976, Ferguson and Adams 1979, Gordon 1973, McCaughey and Schmidt 1982, Seidel 1983). More information is needed, however, regarding the growth rates that can be expected and how soon a response will occur in various plant communities and for species other than fir or spruce. Of particular interest is mountain hemlock because of the lack of growth data for this species and the increasing interest in its management.

The purpose of this study was to obtain data on diameter and height growth response of advance reproduction of suppressed true fir and mountain hemlock after overstory removal in several mixed conifer communities on the east slope of the Cascade Range. Specific study objectives were: (1) to determine and compare rates of diameter and height growth before and after release for each species, (2) to determine how soon after release the increased growth response occurs, and (3) to screen specific variables to use in models for predicting diameter and height growth. This study expands on an earlier study that was limited to one species and a single stand (Seidel 1980b).

Study Area

Study areas were clearcut and shelterwood units and adjacent uncut stands located in midslope to upperslope mixed conifer forests in the Deschutes National Forest in Deschutes County and Winema National Forest in Klamath County (fig. 1). Two plant communities are present on the study areas (Volland 1982): (1) a mountain hemlock/grouse huckleberry community and (2) a mixed conifer/snowbrush-chinkapin community. Elevations ranged from 1524 to 1950 meters (5,000 to 6,400 ft) and slopes ranged from 0 to 25 percent on all aspects.

Study areas were within the pumice plateau region of south-central Oregon. Soils in this region are immature Regosols (Vitrandepts) developed from aerially deposited dacite and rhyolitic pumice ejected from Mount Mazama (Crater Lake) about 6,500 years ago. These well-drained, coarse-textured soils have thin infertile A-horizons that grade into unweathered sand and gravel. A finer textured buried soil is found at a depth of 0.6 to 1.8 meters (2 to 6 ft) (Larsen 1976).

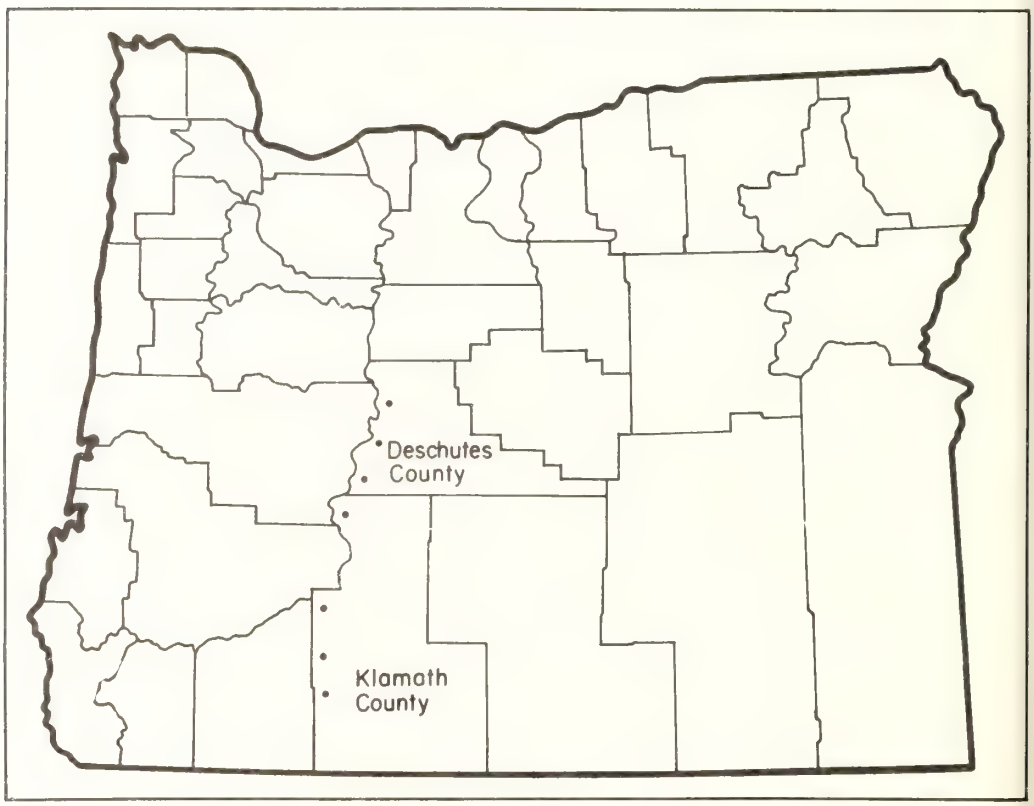

Figure 1.—Counties where study areas are located in south-central Oregon; three stands were sampled in the vicinity of each dot.

Table 1—Mean and range of some characteristics of true fir and mountain hemlock advance reproduction in uncut, shelterwood, and clearcut units, Cascade Range, south-central Oregon, in 1983

	Uncut				Shelterwood				Clearcut			
	True fir		Mountain hemlock		True fir		Mountain hemlock		True fir		Mountain hemlock	
Characteristic	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Diameter (d.b.h.) (centimeters)	3.4	0.5-12.3	3.8	0.5-14.7	3.5	0.5-8.1	4.1	1.3-8.4	4.1	0.5-11.7	5.2	1.0-10.5
Total height (meters)	2.38	.76-5.64	2.74	.76-5.54	2.29	1.07-4.11	2.68	1.06-4.42	2.77	.76-5.94	3.54	1.98-5.33
Live crown ratio (percent)	65	8-95	71	50-94	62	31-97	71	43-95	77	34-100	89	61-100
Total age (years)	92	21-260	104	56-250	74	26-179	109	45-196	87	16-171	73	27-134
Years to reach breast height of 137 centimeters	76	10-217	87	17-129	61	21-124	90	11-123	64	12-149	61	17-111

Species composition of the old-growth mixed conifer community consisted of about 52 percent grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), 23 percent Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), 17 percent Shasta red fir (*Abies magnifica* var. *shastensis* Lemm.), 5 percent ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) plus a few lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), western white pine (*Pinus monticola* Dougl. ex D. Don), and Engelmann spruce. In the mountain hemlock community, 51 percent of the overstory was mountain hemlock, 35 percent red fir, 6 percent grand fir, 5 percent white pine, and small numbers of spruce, lodgepole pine, and Douglas-fir. These stands were over 300 years old and averaged about 36 square meters per hectare of basal area (157 ft^2/acre) in the mountain hemlock type and 24 square meters per hectare (105 ft^2/acre) in the mixed conifer community.

Some characteristics of the suppressed understory trees derived from stem analysis are given in table 1. Height of the firs (grand fir and red fir) ranged from 0.8 to 5.9 meters (2.6 to 19.4 ft) and the mountain hemlock sampled were from 0.8 to 5.6 meters (2.6 to 18.4 ft) tall. Total age of sample trees ranged from 21 to 260 years for fir and from 27 to 250 years for mountain hemlock.

Methods

Eight clearcuttings, six shelterwoods, and nine uncut areas were sampled in this study. The units were selected from among a larger number of units used in an earlier study that described the status of regeneration in mixed conifer communities in the Cascade Range in Oregon. The sampling design and criteria for selecting these units are given in earlier reports (Seidel 1979a, 1979b).

In 1983, a grid of 12 sample points spaced 50 meters (165 ft) apart was centrally located on each of the clearcut, shelterwood, and uncut units suitable for this study. To qualify as study areas, harvesting on cutting units must have occurred at least 10 years prior and have left at least 790 trees per hectare (320 per acre) of advance reproduction after logging. At each sample point, the true fir and mountain hemlock closest to the point were selected for sampling, subject to the following qualifications: (1) the tree had to be less than 6 meters (20 ft) tall, and (2) the tree had to be free of damage from logging and from dwarf mistletoe (*Arceuthobium* spp.). Because both a true fir and mountain hemlock were not found at every sample point, this procedure resulted in a total of 322 sample trees: 201 firs and 121 hemlock. Trees (both species combined) were distributed on cutting units as follows: clearcut—101; shelterwood—74; and uncut—147.

Trees selected for sampling were cut at ground level and the following measurements taken in the field:

1. D.b.h. (diameter at breast height).

2. Total height.

3. Live crown length. (The base of the live crown was defined as the point where at least two branches of a whorl were present. Single isolated branches below the main crown were not included.)

The overstory density (basal area) was measured at the location of each tree using a 10-factor basal area gauge. Aspect, slope percentage, and elevation were also recorded for each tree.[1/]

Sample trees were then brought into the laboratory and stem analysis was used to determine the size and age of the tree at the time of release (initial values) and the annual diameter and height growth for a 5-year period before release (preharvest) and a 5-, 10-, 15-, or 20-year period after release (postharvest).

[1/] Aspect was coded by the method proposed by Day and Monk (1974) in which the following values were assigned to compass directions: N-14; NE-15; E-11; SE-7; S-3; SW-2; W-6; NW-10.

Diameter and height growth models were developed for individual true fir and mountain hemlock using stepwise regression procedures to fit to the data linear equations of the form:

$$Y = b_o + b_1X_1 + b_2X_2 + \ldots b_nX_n \quad .$$

Dependent (Y) variables were:

- Postharvest, 5-, 10-, 15-, and 20-year diameter growth (millimeters) at ground level
- Postharvest, 5-, 10-, 15-, and 20-year height growth (centimeters)

Independent (X) variables were:

- Preharvest, 5-year diameter growth (millimeters) at ground level
- Preharvest, 5-year height growth (centimeters)
- Postharvest basal area (square meters per hectare)
- Initial diameter (millimeters) at ground level
- Initial height (centimeters)
- Initial crown length (centimeters) determined from aging branches at the base of the crown
- Initial live crown ratio (crown length/total height)
- Initial age (years)
- Aspect (code)
- Slope (percent)
- Elevation (meters)

Regression analysis assumes each tree to be independent and randomly selected from the whole study area. The individual trees used in this study were not completely independent because many trees were selected from each unit. Trees on a single unit are likely to be more similar than trees selected at random from the entire population and, if they are, the residual error about regression will be underestimated.

The sample size for these growth equations varied because not all cutting units had the same number of years of postharvest growth. All units were at least 10 years old, some were 15, and some 20.

Curvilinear equations of the form:

$$Y = a + b\,(1-e^{-cX})^d \quad ;$$

were used to relate average annual diameter and height growth (yearly means) to number of years before and after release for firs and mountain hemlock on clearcut and shelterwood units. After conversion to linear form, these curves were tested for significant differences in slope (b) and level (a) using methods described by Freese (1967). Growth measurements from year to year were not independent; therefore, the residual error about regression may be underestimated.

In 1984, an additional 44 firs and 34 hemlock were collected from the same study areas used in 1983 to provide an independent data set for testing the multiple linear regression growth models developed from the 1983 data. Comparisons of the actual versus the estimated growth on the 1984 data set showed that both diameter and height growth were consistently underestimated from 7 to 93 percent by the models. After this comparison was made, data from both 1983 and 1984 were combined and new regression equations were fitted to the pooled data resulting in a total sample of 400 trees: 245 fir and 155 hemlock.

Results

Diameter Growth Showed Marked Response

Diameter growth of both the firs and mountain hemlock showed a marked response to release compared to the preharvest growth rate. In both clearcut and shelterwood units, the true firs grew faster than hemlock after release; in the uncut stands growth rates were about equal for both species during all five growth periods (fig. 2). As expected, the greatest diameter growth occurred in the clearcuttings, somewhat less in the shelterwood units, and the uncut units showed little change over time. Average growth of hemlock in shelterwood units during the first 5-year period after release was 1.5 times the preharvest growth rate and increased to 2.3 times the preharvest rate during the second 5-year period. Growth of firs in shelterwoods was 1.8 times faster during the first 5-year period compared to the preharvest rate and accelerated to 3.7 times the preharvest rate during the second period.

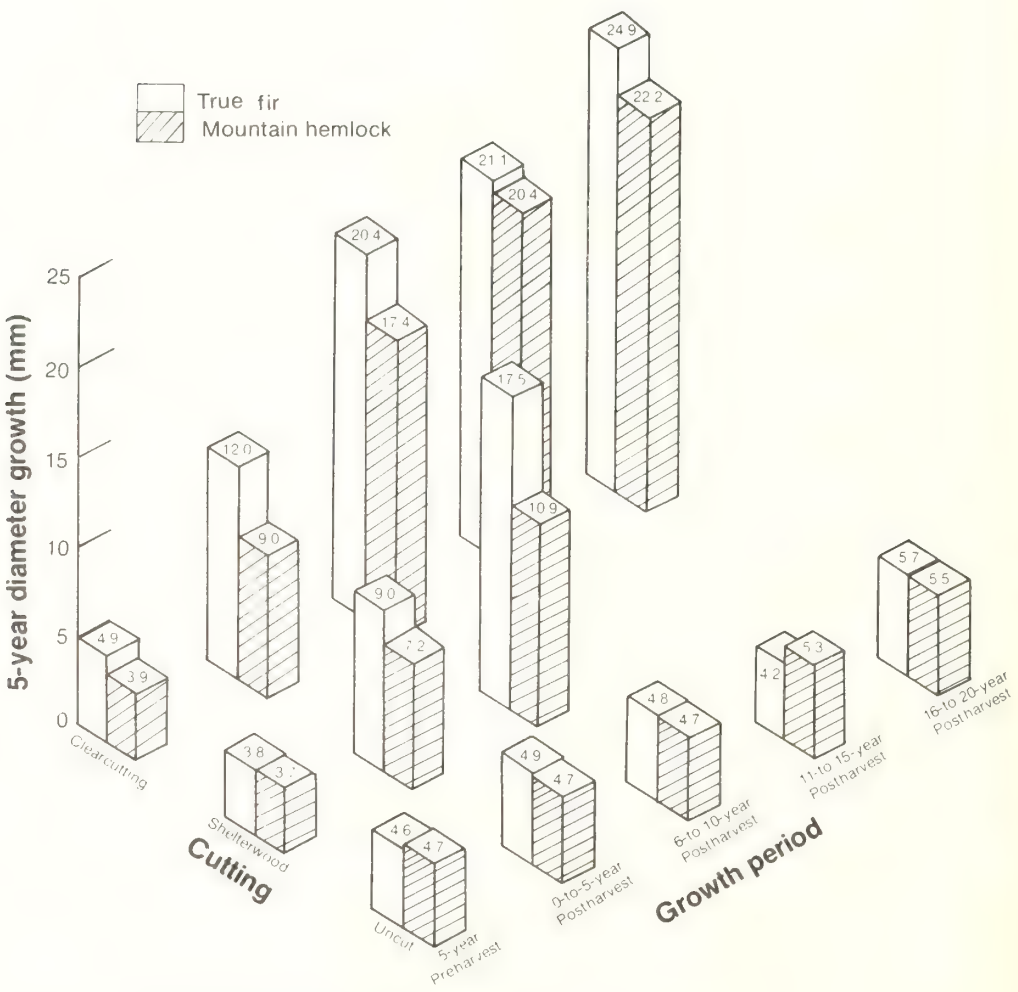

Figure 2.—Periodic diameter growth of true fir and mountain hemlock by cutting method and by preharvest or postharvest 5-year growth period.

In clearcut units, the greater response after release resulted in a growth rate for fir during the first period that was 2.5 times the preharvest rate and reached a maximum of 5.0 times the preharvest rate during the third period. Hemlock responded in a similar, but slightly slower, manner with growth increasing from 1.9 to 4.3 times the preharvest rate from the first to third period after release. The maximum average diameter growth rate of 25 millimeters (1 in) in 5 years occurred on firs in clearcuttings during the fourth growth period (16 to 20 years after release).

In shelterwood units, average annual diameter growth rates of both fir and hemlock were the same before release (fig. 3). After release, the curves diverged, the firs showing a more rapid growth rate and a continuing upward trend after 10 years compared to slower growth of the hemlock and a leveling off of the curve. These curves are significantly different ($P < 0.01$) in both slope and level. Growth rates for both fir and hemlock the second year after release were slightly greater than the prerelease rates but it was not until the third to fourth year after release that a more rapid acceleration in the growth rate occurred. The general pattern of diameter growth after release in the shelterwood units appeared, however, to be a gradual rather than an abrupt increase in growth over time.

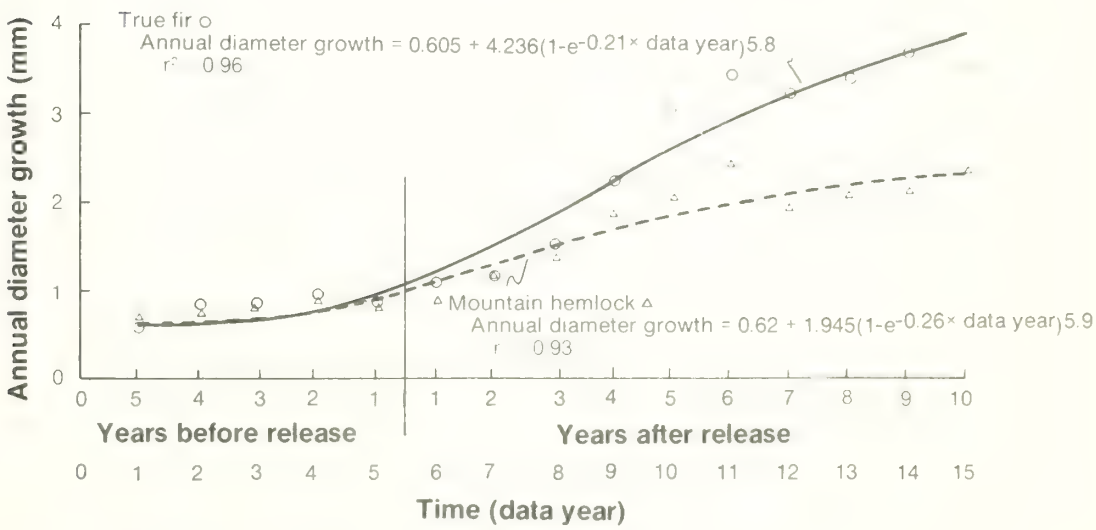
True fir ○
Annual diameter growth = 0.605 + 4.236(1-e-0.21× data year)5.8
r² 0.96
△ Mountain hemlock △
Annual diameter growth = 0.62 + 1.945(1-e-0.26× data year)5.9
r 0.93
Annual diameter growth (mm)
0
1
2
3
4
0 5 4 3 2 1
1 2 3 4 5 6 7 8 9 10
Years before release
Years after release
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Time (data year)

Figure 3.—Annual diameter growth, as a function of time, of true fir and mountain hemlock on shelterwood units. Relationship shows average growth response before and after release for all trees. Mean values for each year were used to calculate equations.

For clearcut units, both fir and hemlock diameter growth curves exhibited the classical sigmoid form showing relatively constant growth before release, a rapid acceleration of growth during the first 8 to 9 years after release, followed by a flattening out of the curves from 10 to 20 years after release (fig. 4). No significant difference in either slope or level was found between these curves. In contrast to the more gradual increase in diameter growth after release found in shelterwood units, diameter growth of both fir and hemlock in these clearcut units showed an immediate response to release. Growth the first year after release was about 1.8 times the 5-year prerelease average growth rate.

The sigmoid form of these growth curves showed that the initial rapid acceleration of diameter growth after release is not maintained. This is clearly seen for clearcut units where growth rates are constant 15 to 20 years after release (fig. 4). Although only 10 years of data after release are available for shelterwoods (fig. 3), the hemlock curves appear to be leveling off and the fir curve, although still rising, will probably begin to level off within the next 10 years.

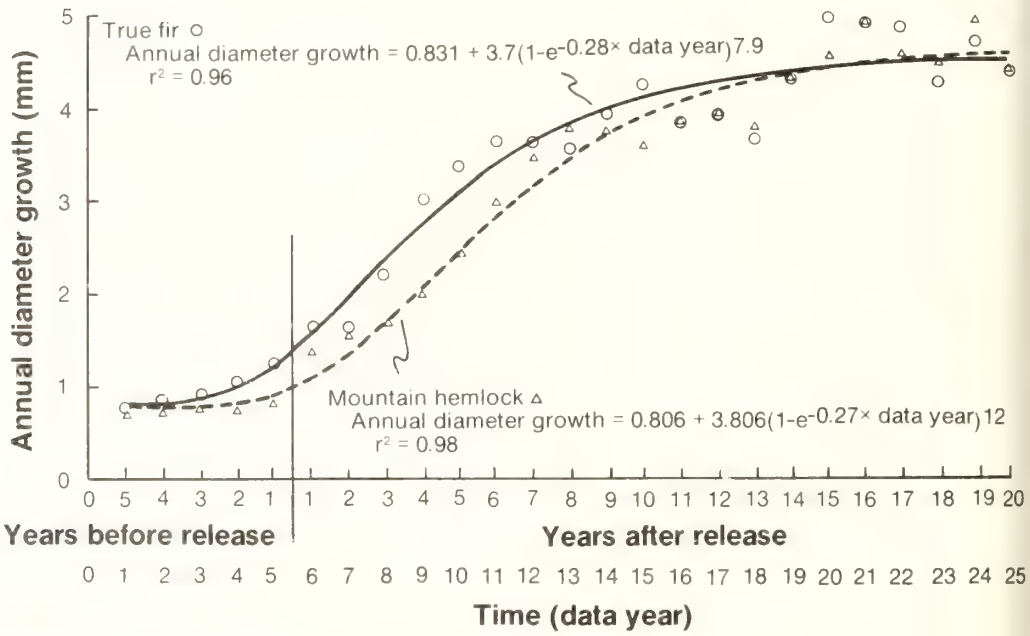
True fir ○
Annual diameter growth = 0.831 + 3.7(1-e-0.28× data year)7.9
r² = 0.96
Mountain hemlock △
Annual diameter growth = 0.806 + 3.806(1-e-0.27× data year)12
r² = 0.98
Annual diameter growth (mm)
0
1
2
3
4
5
0 5 4 3 2 1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Years before release
Years after release
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Time (data year)

Figure 4.—Annual diameter growth, as a function of time, of true fir and mountain hemlock on clearcut units. Relationship shows average growth response before and after release for all trees. Mean values for each year were used to calculate equations.

Table 2—Relationship of independent variables to 5-year, 10-year, 15-year, and 20-year diameter growth of suppressed understory of true fir saplings

Independent variables 1/	Equation	Percent of variation explained (R^2) 2/	Standard error of estimate (Sy·x)
	5-YEAR DIAMETER GROWTH		mm
LCR	3/ y = 0.9573 + 0.1671 (LCR)	0.25	6.1
LCR, BA	y = 6.012 + 0.1191 (LCR) - 0.1587 (BA)	.36	5.7
LCR, BA, HG5	y = 3.330 + 0.1102 (LCR) - 0.1491 (BA) + 0.1368 (HG5)	.43	5.4
LCR, BA, HG5, A	y = 0.3495 + 0.1102 (LCR) - 0.1610 (BA) + 0.1521 (HG5) + 0.3071 (A)	.47	5.2
	10-YEAR DIAMETER GROWTH		
BA	y = 32.972 - 0.6173 (BA)	.28	15.7
BA, LCR	y = 15.431 - 0.4493 (BA) + 0.3095 (LCR)	.39	14.5
BA, LCR, A	y = 9.850 - 0.4763 (BA) + 0.3115 (LCR) + 0.6394 (A)	.42	14.2
BA, LCR, A, HG5	y = 3.610 - 0.4613 (BA) + 0.2940 (LCR) + 0.7384 (A) + 0.1742 (HG5)	.45	13.7
	15-YEAR DIAMETER GROWTH		
BA	y = 50.777 - 1.1125 (BA)	.44	20.8
BA, LCR	y = 26.081 - 0.8340 (BA) + 0.4214 (LCR)	.54	19.0
BA, LCR, HG5	y = 15.254 - 0.7835 (BA) + 0.4008 (LCR) + 0.5793 (HG5)	.58	18.1
BA, LCR, HG5, A	y = 8.770 - 0.3512 (BA) + 0.4187 (LCR) + 0.5251 (HG5) + 0.9377 (A)	.61	17.5
BA, LCR, HG5, A, DG5	y = 7.982 - 0.7978 (BA) + 0.4667 (LCR) + 0.6331 (HG5) + 1.0723 (A) - 1.2841 (DG5)	.64	17.1
	20-YEAR DIAMETER GROWTH		
BA	y = 70.796 - 1.4134 (BA)	.50	25.3
BA, LCR	y = 42.367 - 1.1942 (BA) + 0.4892 (LCR)	.57	23.5
BA, LCR, A	y = 36.479 - 1.2733 (BA) + 0.4251 (LCR) + 1.5923 (A)	.62	22.3
BA, LCR, A, DG5	y = 37.772 - 1.2195 (BA) + 0.4912 (LCR) + 1.7098 (A) - 1.5382 (DG5)	.65	21.6

1/ LCR = live crown ratio (percent); BA = postharvest overstory basal area (in square meters per hectare); HG5 = height growth 5 years before release (in centimeters); A = aspect (code); DG5 = diameter growth 5 years before release (in millimeter). Variables are arranged in the order in which they entered the regressions. Only variables that accounted for major portions of the variation in growth are given. Variables were excluded if they failed to raise R^2 values by at least 2 percent.

2/ All are significant at the 1-percent level.

3/ y = diameter growth in millimeters.

The models predicting 5-, 10-, 15-, and 20-year diameter growth for true firs are given in table 2. For all growth periods, except the 5-year period, the best single variable equation involved basal area of the residual overstory and explained from 28 to 50 percent of the variation in diameter growth. Live crown ratio was the next variable to enter the equations and increased R^2 values about 10 percent. Similar diameter growth models for mountain hemlock are given in table 3. In these models, basal area, and past diameter or height growth accounted for the major portion of the variation in diameter growth.

Estimates of fir and hemlock diameter growth for 10- and 20-year periods after overstory removal, as a function of postharvest basal area and live crown ratio, are given in appendix tables 6 and 7. These models are less sensitive than the more complete models given in tables 2 and 3 but both basal area and live crown ratio account for a considerable amount of total variation and can easily be measured in the field.

Table 3—Relationship of independent variables to 5-year, 10-year, 15-year, and 20-year diameter growth of suppressed understory of mountain hemlock saplings

Independent variables 1/	Equation	Percent of variation explained (R^2) 2/	Standard error of estimate (Sy·x)
	5-YEAR DIAMETER GROWTH		mm
DG5	3/ y = 3.351 + 1.0882 (DG5)	0.15	6.4
DG5, BA	y = 5.618 + 1.2321 (DG5) - 0.1550 (BA)	.31	5.8
DG5, BA, A	y = 4.309 + 1.1573 (DG5) - 0.1606 (BA) + 0.1809 (A)	.33	5.7
	10-YEAR DIAMETER GROWTH		
BA	y = 27.422 - 0.4144 (BA)	.24	13.4
BA, DG5	y = 19.922 - 0.4473 (BA) + 1.8978 (DG5)	.33	12.6
BA, DG5, HG5	y = 18.196 - 0.4375 (BA) + 1.4105 (DG5) + 0.2048 (HG5)	.35	12.5
	15-YEAR DIAMETER GROWTH		
BA	y = 47.832 - 0.8750 (BA)	.39	19.5
BA, HG5	y = 34.259 - 0.7971 (BA) + 0.7276 (HG5)	.46	18.4
BA, HG5, AGE	y = 28.161 - 0.9096 (BA) + 0.7347 (HG5) + 0.1040 (AGE)	.49	18.0
BA, HG5, AGE, LCR	y = 1.957 - 0.8071 (BA) + 0.7167 (HG5) + 0.1308 (AGE) + 0.3111 (LCR)	.52	17.6
	20-YEAR DIAMETER GROWTH		
BA	y = 66.864 - 1.1536 (BA)	.48	22.4
BA, HG5,	y = 45.542 - 1.0100 (BA) + 1.0389 (HG5)	.60	19.9
BA, HG5, LCR	y = 10.395 - 0.8410 (BA) + 1.0058 (HG5) + 0.4523 (LCR)	.65	18.6
BA, HG5, LCR, E	y = 156.531 - 0.8062 (BA) + 0.9065 (HG5) + 0.4432 (LCR) - 0.0763 (E)	.69	17.8
BA, HG5, LCR, E, AGE	y = 162.973 - 0.9644 (BA) + 0.8613 (HG5) + 0.5291 (LCR) - 0.0865 (E) + 0.1341 (AGE)	.72	17.2

1/ DG5 = diameter growth 5 years before release (in millimeters); BA = postharvest overstory basal area (in square meters per hectare); A = aspect (code); HG5 = height growth 5 years before release (in centimeters); Age = total age of tree (years); LCR = live crown ratio (percent); E = elevation (in meters). Variables are arranged in the order in which they entered the regressions. Only variables that accounted for major portions of the variation in growth are given. Variables were excluded if they failed to raise R^2 values by at least 2 percent.

2/ All are significant at the 1-percent level.

3/ y = diameter growth in millimeters.

Height Growth Showed Similar Response

Height growth of both fir and hemlock after release increased over the prerelease rate at a rate similar to the diameter growth response. In shelterwood and uncut units, average height growth of the firs was somewhat greater than that of hemlock during all periods except for the uncut units during the 11- to 15-year postharvest period (fig. 5). In clearcut units, this relationship was reversed; average growth of hemlock exceeded that of fir during the preharvest period and during all postharvest periods. Acceleration of growth after release began slowly during the first period, showing no change for fir in shelterwood units compared to uncut units. Height growth rates increased in subsequent periods for both fir and hemlock and reached a maximum of 4.8 times the prerelease rate for hemlock in clearcuttings during the fourth period. Actual growth during this 5-year period averaged 65 centimeters (25.5 in) for fir and 79 centimeters (31.1 in) for hemlock. This corresponds to a periodic annual growth rate of 13 centimeters (5.1 in) and 16 centimeters (6.2 in), respectively.

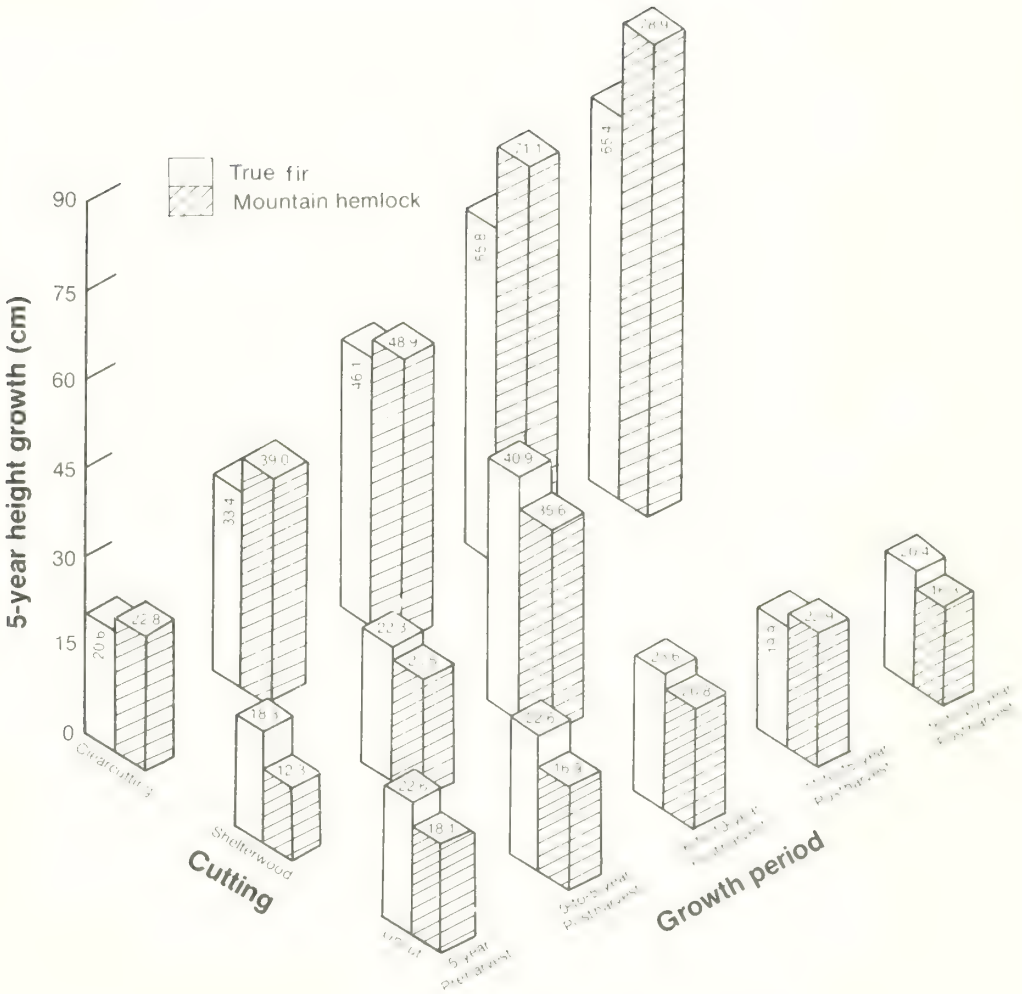

Figure 5.—Periodic height growth of true fir and mountain hemlock by cutting method and by preharvest or postharvest 5-year growth period.

The annual height growth curves for fir and hemlock in shelterwood units have common slopes but differ significantly ($P < 0.01$) in levels with fir having more rapid growth than hemlock both before and after release (fig. 6). An increase in growth for fir was not evident until the fourth year after release (when it was 1.4 times the 5-year prerelease average), while hemlock showed this same increase 2 years after release.

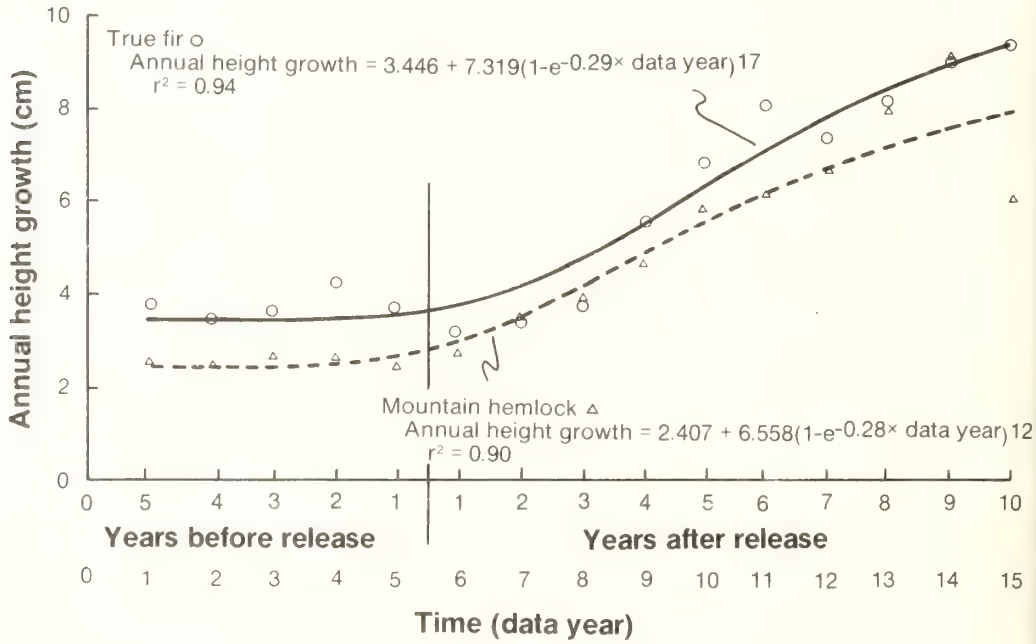
True fir ○
Annual height growth = 3.446 + 7.319(1-e-0.29× data year)17
r² = 0.94
Mountain hemlock △
Annual height growth = 2.407 + 6.558(1-e-0.28× data year)12
r² = 0.90
Annual height growth (cm)
Years before release
Years after release
Time (data year)

Figure 6.—Annual height growth, as a function of time, of true fir and mountain hemlock on shelterwood units. Relationship shows average growth response before and after release for all trees. Mean values for each year were used to calculate equations.

In clearcut units, fir and hemlock curves differed significantly (P· 0.01) in both slope and level (fig. 7). Height growth of hemlock was greater than that of fir especially 10 to 20 years after release when hemlock grew 1.3 times faster than fir. A rapid acceleration in growth of hemlock occurred the first year after release (1.5 times the prerelease rate), but increased growth of fir was delayed until the third year after release. Similar to the diameter growth curves, the height growth curves display the same sigmoid relationship with growth rates tending to level off during the third and fourth 5-year periods after release.

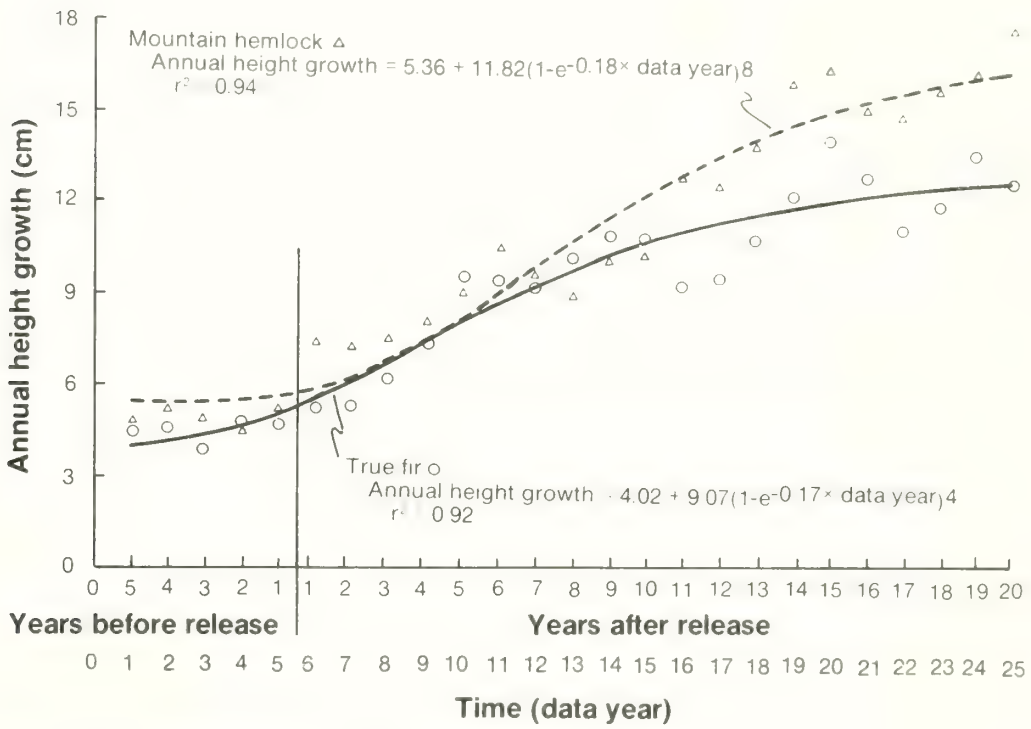
Mountain hemlock △
Annual height growth = 5.36 + 11.82(1-e-0.18× data year)8
r² 0.94
True fir ○
Annual height growth · 4.02 + 9.07(1-e-0.17× data year)4
r² 0.92
Annual height growth (cm)
Years before release
Years after release
Time (data year)

Figure 7.—Annual height growth, as a function of time, of true fir and mountain hemlock on clearcut units. Relationship shows average growth response before and after release for all trees. Mean values for each year were used to calculate equations.

Table 4—Relationship of independent variables to 5-year, 10-year, 15-year, and 20-year height growth of suppressed understory of true fir saplings

Independent variables 1/	Equation	Percent of variation explained (R^2) 2/	Standard error of estimate ($S_{y \cdot x}$)
	5-YEAR HEIGHT GROWTH		cm
HG5	3/ y = 7.724 + 0.9329 (HG5)	0.30	19.5
HG5, AGE	y = 23.644 + 0.8244 (HG5) - 0.2045 (AGE)	.39	18.2
HG5, AGE, LCR	y = 11.383 + 0.7875 (HG5) - 0.1791 (AGE) + 0.2410 (LCR)	.44	17.6
	10-YEAR HEIGHT GROWTH		
HG5	y = 28.336 + 1.8201 (HG5)	.20	49.8
HG5, LCR	y = -10.882 + 1.6277 (HG5) + 0.9195 (LCR)	.32	46.0
HG5, LCR, AGE	y = 30.297 + 1.4133 (HG5) + 0.7869 (LCR) - 0.4564 (AGE)	.40	43.4
	15-YEAR HEIGHT GROWTH		
BA	y = 132.800 - 2.3210 (BA)	.33	54.7
BA, HG5	y = 83.554 - 2.0585 (BA) + 2.3701 (HG5)	.46	49.2
BA, HG5, LCR	y = 39.746 - 1.5506 (BA) + 2.2566 (HG5) + 0.7878 (LCR)	.52	46.7
BA, HG5, LCR, CL	y = 30.536 - 1.2345 (BA) + 2.3905 (HG5) + 1.3966 (LCR) - 0.3848 (CL)	.57	44.3
BA, HG5, LCR, CL, A	y = 16.801 - 1.4085 (BA) + 2.2560 (HG5) + 1.3913 (LCR) - 0.3563 (CL) + 2.1964 (A)	.60	43.2
	20-YEAR HEIGHT GROWTH		
BA	y = 190.061 - 2.9819 (BA)	.38	66.9
BA, A	y = 159.983 - 3.1396 (BA) + 4.9812 (A)	.47	62.7
BA, A, HG5	y = 113.326 - 2.9398 (BA) + 4.7823 (A) + 2.3477 (HG5)	.54	58.8
BA, A, HG5, LCR	y = 67.562 - 2.5424 (BA) + 4.1987 (A) + 2.3637 (HG5) + 0.8425 (LCR)	.58	56.7
BA, A, HG5, LCR, TH	y = 78.657 - 2.0345 (BA) + 4.0684 (A) + 2.9068 (HG5) + 0.9595 (LCR) - 0.2422 (TH)	.62	54.3
BA, A, HG5, LCR, TH, DG5	y = 74.161 - 1.8772 (BA) + 4.2991 (A) + 3.2832 (HG5) + 1.1109 (LCR) - 0.2440 (TH) - 3.4615 (DG5)	.65	52.9

1/ HG5 = height growth 5 years before release (in centimeters); AGE = total age of tree (years); LCR = live crown ratio (percent); BA = postharvest overstory basal area (in square meters per hectare); CL = crown length (in centimeters); A = aspect (code); TH = total height (in centimeters); DG5 = diameter growth 5 years before release (in millimeters). Variables are arranged in the order in which they entered the regressions. Only variables that accounted for major portions of the variation in growth are given. Variables were excluded if they failed to raise R^2 values by at least 2 percent.

2/ All are significant at the 1-percent level.

3/ y = height growth in centimeters.

Stepwise regression models predicting 5-, 10-, 15-, and 20-year height growth for true firs are given in table 4. As with diameter growth models, basal area, past height growth, and live crown ratio are important variables for predicting height growth. Total age in the 5-year model and aspect in the 20-year model enter as the second variable. Residual overstory basal area and past 5-year height growth were the two variables accounting for most of the variation in the hemlock height growth models (table 5). Height growth estimates based on the two-variable model (basal area and live crown ratio) are given in appendix tables 8 and 9.

Table 5—Relationship of independent variables to 5-year, 10-year, 15-year, and 20-year height growth of suppressed understory of mountain hemlock saplings

Independent variables 1/	Equation	Percent of variation explained (R^2) 2/	Standard error of estimate (Sy·x)
	5-YEAR HEIGHT GROWTH		cm
HG5	3/ y = 9.779 + 0.9585 (HG5)	0.24	19.6
HG5, BA	y = 17.590 + 0.9517 (HG5) - 0.4135 (BA)	.35	18.1
HG5, BA, TH	y = 24.159 + 0.9786 (HG5) - 0.3295 (BA) - 0.0468 (TH)	.39	17.7
HG5,BA, TH, DG5	y = 22.227 + 0.7639 (HG5) - 0.3375 (BA) - 0.0633 (TH) + 2.0881 (DG5)	.42	17.3
	10-YEAR HEIGHT GROWTH		
BA	y = 88.066 - 1.2025 (BA)	.17	48.4
BA, HG5	y = 55.728 - 1.1904 (BA) + 1.8140 (HG5)	.32	43.7
BA, HG5, TH	y = 71.188 - 0.9930 (BA) + 1.8771 (HG5) - 0.1101 (TH)	.36	42.8
BA, HG5, TH, DG5	y = 66.910 - 1.0104 (BA) + 1.4019 (HG5) - 0.1467 (TH) + 4.6233 (DG5)	.39	41.9
	15-YEAR HEIGHT GROWTH		
BA	y = 157.090 - 2.7159 (BA)	.41	58.5
BA, HG5	y = 96.671 - 2.3692 (BA) + 3.2391 (HG5)	.56	50.9
	20-YEAR HEIGHT GROWTH		
BA	y = 237.416 - 4.2349 (BA)	.49	80.1
BA, HG5	y = 146.134 - 3.6200 (BA) + 4.4479 (HG5)	.66	66.3
BA, HG5, E	y = 806.311 - 3.4476 (BA) + 3.9941 (HG5) - 0.3463 (E)	.72	61.0

1/ HG5 = height growth 5 years before release (in centimeters); BA = postharvest overstory basal area (in square meters per hectare); TH = total height (in centimeters); DG5 = diameter growth 5 years before release (in centimeters); E = elevation (in meters). Variables are arranged in the order in which they entered the regressions. Only variables that accounted for major portions of the variation in growth are given. Variables were excluded if they failed to raise R^2 values by at least 2 percent.

2/ All are significant at the 1-percent level.

3/ y = height growth in centimeters.

Because height growth before release is an important variable in the true fir height growth models (table 4), height growth estimates for true fir based on basal area and past 5-year height growth are given in table 10 (appendix). The models give somewhat higher R^2 values and lower standard errors than do the models based on live crown ratio (tables 8 and 9). Past height growth is also a significant variable for predicting height growth of hemlock but estimates based on past height growth are not given for mountain hemlock because annual internodes cannot be identified in the field on standing trees.

In addition to obtaining data on the most recent growth periods of these trees (immediately before and after release), the stem analysis procedure provided an opportunity to determine the seedling height growth pattern—the number of years required for trees to reach a breast height of 137 centimeters (4.5 ft). The average number of years for both fir and hemlock to reach breast height varied from 54 to 76 years (table 1) and the overall mean was 62 years for fir and 58 years for hemlock. This corresponds to a mean height growth rate of about 2.3 centimeters (0.9 in) per year during the seedling establishment period. Although the average growth rate is relatively uniform, the growth rate of individual trees varies widely. The extremes of height growth are illustrated by the data for fir in uncut stands where 10 to 217 years were needed for trees to reach breast height or a growth rate of from 13.7 centimeters (5.4 in) to 0.63 centimeters (0.25 in) per year.

Discussion

The results of this study show clearly that advance reproduction of both true fir and mountain hemlock respond in the same manner to release. Diameter and height growth of fir and hemlock saplings are directly proportional to tree vigor, as measured by live crown ratio or height growth before release, and inversely proportional to overstory stand density. In other words, the greatest growth occurred on full-crowned trees in clearcuttings; growth was intermediate in shelterwood units and slowest in uncut stands. Based on average growth rates, it is reasonable to expect an increase in diameter and height growth after release of from two to four times the prerelease growth rate for both fir and hemlock. Increased growth rates generally occur within 5 years after release, reach a maximum after about 10 years, and continue at this rate for at least 20 years.

Both firs and mountain hemlock responded to release with dramatic diameter growth increases regardless of age. The greatest growth response was found on a 150-year-old grand fir that grew 2.6 centimeters (1 in) in diameter during the 133 years before release and 9.2 centimeters (3.6 in) in 17 years after release— a postrelease growth rate about 27 times the prerelease rate. A 186-year-old mountain hemlock increased its diameter growth rate about 19 times from 7.2 centimeters (2.8 in) during the 168-year prerelease period to 14.7 centimeters (5.8 in) during the 18-year postrelease period.

One factor to consider in evaluating the comparative advantage of advance reproduction versus planted seedlings or natural regeneration is the height growth rates of each type of regeneration (Seidel 1980a). The height growth estimates given in appendix tables 8, 9, and 10 provide some of the information needed to make such an evaluation for mixed conifer and mountain hemlock communities on the east slope of the Oregon Cascade Range. The diameter and height growth models developed in this study were not validated with an independent data set because the additional data collected in 1984 were used to improve the original models. Those using these models should, therefore, test them by comparing actual growth observed on released trees with the estimated growth to determine if the models give reasonable estimates.

Another important factor to consider when evaluating the suitability of suppressed grand fir or white fir for future crop trees is the potential of future volume losses caused by the Indian paint fungus (*Echinodontium tinctorium* E & E). Filip and others (1983) have prepared guidelines for reducing heartrot losses from this disease. They recommend selecting vigorous crop trees based on a live crown ratio of at least 50 percent and current annual height growth of at least 20 centimeters (8 in). In my study, the maximum average annual height growth of fir in clearcuttings was about 13 centimeters (5 in) 20 years after release, although 30 percent of the firs sampled in clearcuttings grew 20 centimeters (8 in) or more in height during their last growing season.

It is now apparent from studies of the response of suppressed advance reproduction to release in various plant communities in the west that shade tolerant species, such as firs, spruces, and hemlocks, have the capacity to greatly increase diameter and height growth after overstory removal or after thinning. It is also evident that the most vigorous trees grow the fastest and that the two individual tree variables most strongly correlated with tree vigor are live crown ratio and past 5-year height growth (Ferguson and Adams 1979, McCaughey and Schmidt 1982, Seidel 1980b). Thus, advance reproduction can easily be evaluated in the field to determine its management potential. Selecting only vigorous reproduction for management not only results in the greatest growth response after overstory removal but also in the most protection against heartrots because rapidly growing trees are better able to compartmentalize any decay columns resulting from wounding of the tree (Shigo and Marx 1977).

Conversion Factors

1 meter = 3.2808 feet
1 centimeter = 0.3937 inches
1 millimeter = 0.03937 inches
1 square meter per hectare = 4.356 square feet per acre

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Appendix

Table 6—10-year diameter growth estimates of suppressed understory of true fir and mountain hemlock as a function of live crown ratio and residual overstory basal area[1/]

	Live crown ratio									
Residual basal area	10	20	30	40	50	60	70	80	90	100
Square meters per hectare	Millimeters									
	TRUE FIR									
0	19	22	25	28	31	34	37	40	43	46
9.2	14	17	21	24	27	30	33	36	39	42
18.4	11	14	17	20	23	26	29	32	35	38
27.5	7	10	13	16	19	22	25	28	31	34
36.7	3	6	9	12	15	18	21	24	27	30
45.9		1	4	7	10	13	16	19	22	25
$y = 15.431 + 0.3095\ X_1 - 0.4493\ X_2$							$R^2 = 0.39$; n = 245; Sy·x = 14.5 mm			
	MOUNTAIN HEMLOCK									
0	12	14	16	19	21	23	26	28	30	33
9.2	9	11	13	16	18	20	23	25	27	30
18.4	5	8	10	12	15	17	20	22	24	27
27.5	2	5	7	9	12	14	17	19	21	24
36.7		2	4	6	9	11	14	16	18	21
45.9			1	3	5	7	10	12	14	17
$y = 9.313 + 0.2344\ X_1 - 0.3378\ X_2$							$R^2 = 0.29$; n = 155; Sy·x = 13.0 mm			

[1/] Limits of basic plot data enclosed within solid line.
y = 10-year diameter growth, in millimeters;
X_1 = live crown ratio; and
X_2 = residual basal area, in square meters per hectare.

Table 7—20-year diameter growth estimates of suppressed understory of true fir and mountain hemlock as a function of live crown ratio and residual overstory basal area[1/]

Residual basal area	Live crown ratio									
	10	20	30	40	50	60	70	80	90	100
Square meters per hectare	Millimeters									
	TRUE FIR									
0	47	52	57	62	67	72	77	82	86	91
9.2	36	41	46	51	56	61	66	71	75	80
18.4	25	30	35	40	45	50	55	60	64	69
27.5	14	19	24	29	34	39	44	49	53	58
36.7	3	8	13	18	23	28	33	38	42	47
45.9			2	7	12	17	22	27	31	36
$y = 42.367 + 0.4892\ X_1 - 1.1942\ X_2$								$R^2 = 0.57$; n = 65; $Sy{\cdot}x = 23.5$ mm		
	MOUNTAIN HEMLOCK									
0	33	38	43	48	53	58	62	67	72	77
9.2	25	29	34	39	44	49	54	58	63	68
18.4	15	20	25	30	35	40	44	49	54	59
27.5	6	11	16	21	26	31	35	40	45	50
36.7		2	7	12	17	22	26	31	36	41
45.9				4	9	14	18	23	28	33
$y = 28.620 + 0.4828\ X_1 - 0.9681\ X_2$								$R^2 = 0.54$; n = 63; $Sy{\cdot}x = 21.2$ mm		

1/ Limits of basic plot data enclosed within solid line.
$\bar{y}$ = 20-year diameter growth, in millimeters;
X_1 = live crown ratio; and
X_2 = residual basal area, in square meters per hectare.

Table 8—10-year height growth estimates of suppressed understory of true fir and mountain hemlock as a function of live crown ratio and residual overstory basal area[1/]

Residual basal area	Live crown ratio									
	10	20	30	40	50	60	70	80	90	100
Square meters per hectare	Centimeters									
	TRUE FIR									
0	55	62	70	78	86	94	101	109	117	125
9.2	46	54	62	69	77	85	93	101	108	116
18.4	38	45	53	61	69	77	84	92	100	108
27.5	30	37	45	53	61	69	76	84	92	100
36.7	21	28	36	44	52	60	67	75	83	91
45.9	13	20	28	36	44	52	59	67	75	83
$y = 46.812 + 0.7796\ X_1 - 0.9235\ X_2$							$R^2 = 0.22$; n = 245; Sy·x = 49.2 cm			
	MOUNTAIN HEMLOCK									
0	28	37	46	55	64	73	82	91	100	109
9.2	19	28	37	46	55	64	73	82	91	101
18.4	11	20	29	38	47	56	65	74	83	92
27.5	3	12	21	30	39	48	57	66	75	84
36.7		4	13	22	31	40	49	58	67	76
45.9			4	13	22	31	40	49	58	67
$y = 18.704 + 0.8981\ X_1 - 0.9089\ X_2$							$R^2 = 0.23$; n = 155; Sy·x = 46.6 cm			

1/ Limits of basic plot data enclosed within solid line.
y = 10-year height growth, in centimeters;
X_1 = live crown ratio; and
X_2 = residual basal area, in square meters per hectare.

Table 9—20-year height growth estimates of suppressed understory of true fir and mountain hemlock as a function of live crown ratio and residual overstory basal area[1/]

Residual basal area	Live crown ratio									
	10	20	30	40	50	60	70	80	90	100
Square meters per hectare	Centimeters									
	TRUE FIR									
0	141	152	162	172	182	192	202	212	222	232
9.2	118	128	138	149	159	169	179	189	199	209
18.4	94	105	115	125	135	145	155	165	175	185
27.5	71	82	92	102	112	122	132	142	152	162
36.7	48	59	69	79	89	99	109	119	129	139
45.9	25	36	46	56	66	76	86	96	106	116
$y = 131.395 + 1.0095\ X_1 - 2.5295\ X_2$								$R^2 = 0.44$; n = 65; Sy·x = 64.1 cm		
	MOUNTAIN HEMLOCK									
0	190	197	203	210	217	224	231	238	245	252
9.2	153	160	167	174	181	188	195	201	208	215
18.4	117	124	130	137	144	151	158	165	172	179
27.5	81	88	94	101	108	115	122	129	136	143
36.7	44	51	57	64	71	78	85	92	99	106
45.9	7	15	21	28	35	42	49	56	63	70
$y = 182.815 + 0.6893\ X_1 - 3.9700\ X_2$								$R^2 = 0.50$; n = 63; Sy·x = 80.0 cm		

1/ Limits of basic plot data enclosed within solid line.
$\bar{y}$ = 20-year height growth, in centimeters;
X_1 = live crown ratio; and
X_2 = residual basal area, in square meters per hectare.

Table 10—10 and 20-year height growth estimates of suppressed understory of true fir as a function of past 5-year height growth and residual overstory basal area[1/]

Residual basal area	Past 5-year height growth (in centimeters)							
	5	15	25	35	45	55	65	75
Square meters per hectare	Centimeters							
	10-YEAR HEIGHT GROWTH							
0	61	77	94	110	127	143	160	176
9.2	50	67	83	100	116	133	149	166
18.4	39	55	72	88	105	121	138	154
27.5	29	45	62	78	95	111	128	144
36.7	18	34	51	67	84	100	117	133
45.9	7	23	40	56	73	89	106	122
55.1		12	29	45	62	78	95	111
64.3		2	19	35	52	68	85	101
$y = 52.546 + 1.652\ X_1 - 1.173\ X_2$					$R^2 = 0.31$; n = 245; $Sy{\cdot}x = 46.4$ cm			
	20-YEAR HEIGHT GROWTH							
0	152	177	201	206	250	275	299	324
9.2	127	151	176	200	225	249	274	298
18.4	101	126	150	175	199	224	248	273
27.5	76	101	125	150	174	199	223	248
36.7	50	75	99	124	148	173	197	222
45.9	24	49	73	98	122	147	171	196
55.1		24	48	73	97	122	146	171
64.3			22	47	71	96	120	145
$y = 140.072 + 2.4523\ X_1 - 2.7798\ X_2$					$R^2 = 0.46$; n = 65; $Sy{\cdot}x = 63.0$ cm			

1/ Limits of basic plot data within solid line.
$\bar{y}$ = height growth, in centimeters;
X_1 = past 5-year height growth, in centimeters; and
X_2 = residual basal area, in square meters per hectare.

*GPO 691 - 230 (1985)

Seidel, K. W. Growth response of suppressed true fir and mountain hemlock after release. Res. Pap. PNW-344. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 22 p.

The diameter and height growth of advance reproduction of suppressed true fir (*Abies* spp.) and mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) was measured in south-central Oregon after release by overstory removal in clearcuttings, shelterwood units, and uncut stands. Postrelease growth was greatest in clearcuttings, intermediate in shelterwood cuttings, and slowest in uncut stands. Multiple regression analyses were used to predict growth response as a function of tree and stand variables. Overstory basal area, live crown ratio, and past 5-year height growth accounted for the most variation in diameter and height growth after release. Vigorous advance reproduction having live crown ratios greater than 50 percent are the best candidates for crop trees.

Keywords: Growth response, release, suppression (tree), advance growth, true fir, mountain hemlock.

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3. 78: PNW-345

United States
Department of
Agriculture

Forest Service

Pacific Northwest
Forest and Range
Experiment Station

Research Paper
PNW-345
November 1985

Tree Form Quotients as Variables in Volume Estimation

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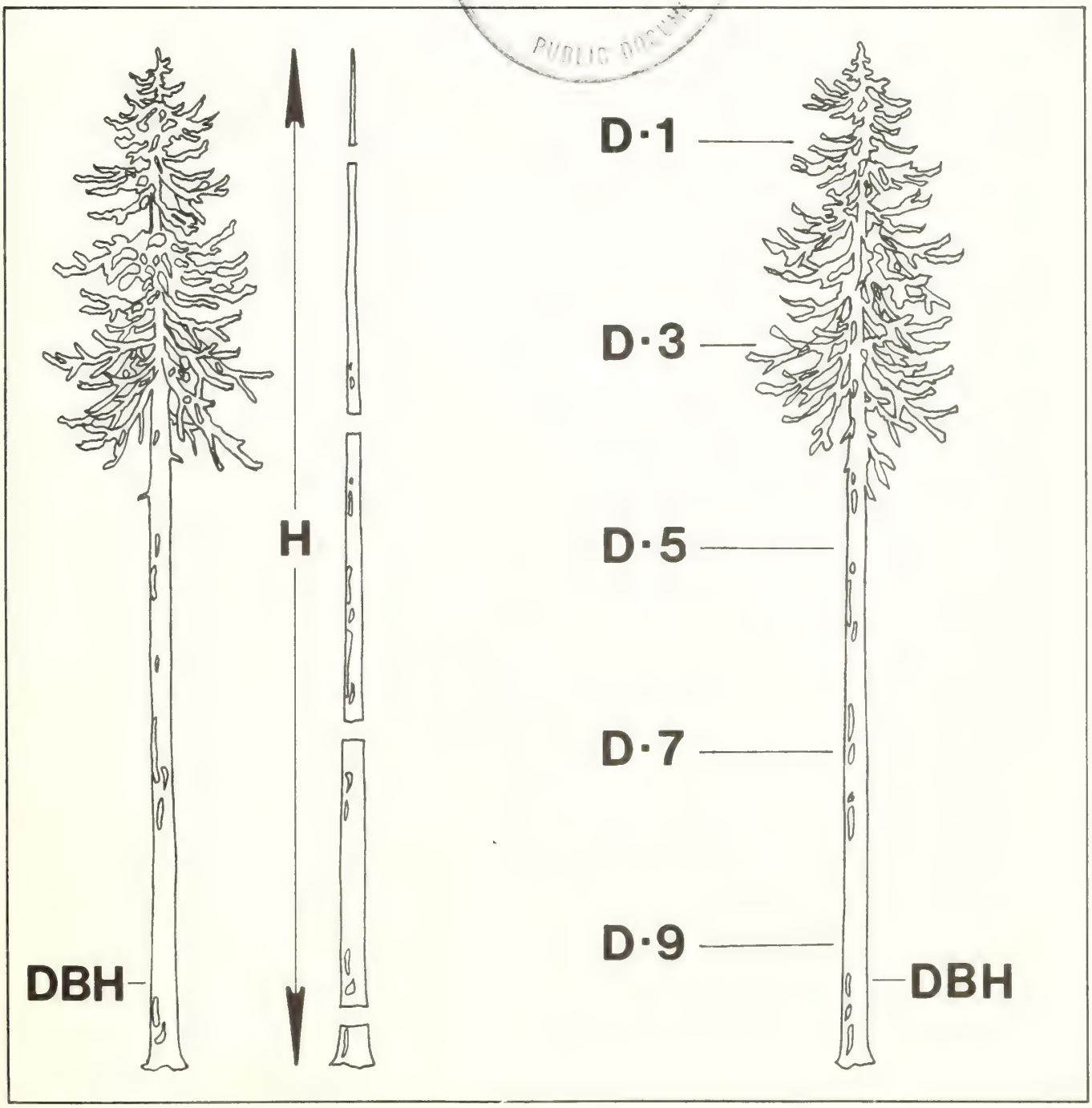
JAN 23 1986
PUBLIC DOCUMENTS



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Abstract

Hoyer, Gerald E. Tree form quotients as variables in volume estimation. Res. Pap. PNW-345. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 16 p.

The study reviews Hohenadl's procedure for defining form quotients and tree volume from diameters measured at fixed proportions of total tree height. Modifications of Hohenadl's procedure were applied to two sets of data for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) from the Pacific Northwest. The procedure was used to define volume differences in thinned stands, and selected form quotients were used as variables to improve accuracy and precision of standard tree volume equations. Estimating form quotients on standing trees requires less time than complete stem dendrometry. The technique has application to other tree species.

Keywords: Volume estimation, volume equations, form factors, form quotient, western hemlock.

Summary

The study briefly reviews Hohenadl's procedure for defining form quotients and estimating tree volume using stem diameters at fixed proportions of total tree height. Hohenadl's procedure was modified to improve accuracy and the modified procedure was used to define volume differences in thinned western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) stands. Selected form quotients were used as variables in tree volume equations.

Young western hemlock stands, 20 feet tall, were thinned to 4-, 9- and 22-foot spacings. Upper stem diameters were measured on standing trees four times during an 8-year period following thinning. A standard volume equation using only tree diameter at breast height and total height overestimated tree volume when compared with that measured using upper stem diameters.

The form quotients (D.5/D.9), (D.9/DBH), (D.7/D.9), and others were calculated for 638 western hemlock sample trees by interpolating for unknown upper stem diameters when measurements at D.5, D.7, and D.9 were missing. Form quotients contributed significantly to accuracy of equations for estimating known tree volume. The quotients identified tree form differences and led to more precise estimates of tree volume than did use of diameter at breast height and tree height alone.

Estimating the form quotients required less time than complete stem dendrometry. The technique described could be used with other species for which stem measurement data are available and for which the specific form quotient measurements may not have been recorded.

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Introduction

Review of Tree Volume Equations

Standard volume tables (equations) are often used to estimate tree volume as a function of tree diameter and height for both routine forest measurement and for forest research purposes. A recognized shortcoming is that a standard volume table (equation) may fail to estimate the volume of sample trees in a specific stand (Evert 1968, Grosenbaugh 1954, Hazard and Berger 1972). This may happen if the actual taper of the sample trees of a stand differs from the average taper of the trees used in construction of the volume equation. Use of these volume equations ignores the variation that occurs because of taper (that is, form) differences.

One solution is to estimate tree volumes with a standard volume equation, then directly measure the volume of a sample of the population of interest using intensive dendrometry. A regression fitted to the data corrects the estimate made by the standard equation. The final result can be thought of as an adjusted local volume table (equation). A complex volume estimation procedure such as three-P sampling (Grosenbaugh 1965) is an efficient specialized parallel to this general procedure. Another parallel uses the results of intensive dendrometry or felled sample tree measurements as access to the tarif volume system (Turnbull and others 1963). The average stand tarif so derived defines the correct local volume equation.

One way to simplify the volume estimating procedure and at the same time improve accuracy of tree volume estimates is to make the standard volume equation sensitive to variation of stem form.

Hohenadl's Technique

The German mensurationist Hohenadl developed a technique for estimating tree volume from diameters measured at proportional distances along the tree bole (Altherr 1960, Assmann 1970, Heger 1965). The measurements lead to form quotients, which describe tree form and also estimate tree volume with a minimum of effort. The technique divides the total tree bole into segments of five lengths, each one-fifth of total height. Diameters measured at midpoints of the five segments are referred to as D.1, D.3, D.5, D.7, and D.9. D.5 is at half the total tree height and D.9 is at 90 percent of the height from the tree tip to the ground. From these stem diameters Hohenadl develops form quotients and tree volume. The rationale of Hohenadl's method is given in the appendix.

Altherr (1960) and Assmann (1970) identify an approximate 4-percent underestimate of tree volume as calculated by Hohenadl's method. Five measurements failed to properly account for flare near the tree base. The underestimate can be corrected by using additional diameters measured at other proportions of tree height near the base of the tree. With nine diameters, tree volume can be estimated within 1 percent of volume estimates that use measurements every 6.6 feet along the total tree stem (Altherr 1960). The rationale of Hohenadl's method holds when additional proportional diameters are used to increase volume precision.

The important point is that several of the form quotients defined by Hohenadl's method are highly correlated with volume (Assman 1970, Heger 1965, Pollanshütz 1966). The form quotients are simple dimensionless ratios of the diameters at selected proportional heights.

It follows logically that if diameters are estimated at several of Hohenadl's proportional heights in an existing body of tree measurements, quotients that characterize tree form can be defined and might allow the existing data to be more useful.

Objectives

There were two objectives for this study:

1. To determine if there is a significant change of lower bole form quotient and volume as the result of initial spacing treatment of young western hemlock (*Tsuga heterophylla* [Raf.] Sarg.).

2. To produce and evaluate volume equations that allow lower bole form quotients to be used along with height and diameter at breast height (DBH) for computing tree volume of western hemlock.

Data Bases

Separate sets of data were used in the two portions of the study. The first set of data was for a spacing study in which stem measurements were made on standing sample trees. The measurements were (1) total tree height, in feet; (2) Hohenadl's (Heger 1965) five diameters at fixed proportions of total tree height, plus (3) four additional diameters as proposed by Altherr (1960). The points of bole diameter measurement, expressed as fractions of the distance from the tree tip down, were: D.1, D.3, D.5, D.7, D.82, D.86, D.9, D.94, and D.98 as well as DBH (4.5 feet above ground). Diameters were measured both outside and inside bark.

The second set of data was for trees collected for volume table construction. Data for 638 sample trees were collected by the Pacific Northwest Forest and Range Experiment Station, USDA Forest Service; the Weyerhaeuser Company; and the State of Washington, Department of Natural Resources. The data were pooled to improve the standard volume equation for western hemlock, and results have been reported (Chambers and Foltz 1979, Wiley and others 1978). The trees had been measured for diameter outside and inside bark beginning at the stump and at 8- to 20-foot intervals thereafter to the tree tip. Tree DBH and total height were also measured.

Study of Form Quotient Change

Methods

Sample tree description.—Initial spacing treatments might cause form quotient and volume differences that would be undetected by tree height and diameter measurements alone. By using special instruments and climbing standing trees, nine bole measurements were made periodically for 4 years of an 8-year period on each of nine trees on two plots in three spacings. Height and DBH were measured annually for the 8 years. The three spacings were 4, 9, and 22 feet. All plots had been spaced to about 4 feet 2 years prior to treatment. Trees averaged 20 feet tall at first treatment and grew to about 45 feet after 8 years.

The use of mean tarif number for volume calculations.—The sample trees are the basis for assigning volume to all trees in a plot at each remeasurement. The procedure for assigning plot volume is the tarif system (Turnbull and others 1963), which uses the recognized linear relationship of tree volume to basal area in even-aged stands (Hummel 1955). From the assortment of volume lines provided by the tarif system, the appropriate volume-basal-area line is selected for each sample tree at each remeasurement. (Established mathematical relationships describe the selection process. Either direct tree measurements or height-diameter-volume equations may be used to estimate tree volume for use in the process.) Each line so selected has a unique, representative tarif number. The average tarif number for all the sample trees on a plot identifies the average volume-basal-area line for each plot.

Mean tarif number at each plot remeasurement is a direct index to the volume line. In this study the tarif procedure was used to compare two sources of the volume line; one was assigned from a standard volume equation and the other was calculated from stem measurements. Expressing the volume lines in terms of mean tarif number allows direct comparison of the sources of volume estimates. Significant differences of mean tarif number between the two sources imply that there is a difference in the underlying relationship of volume to basal area for the sources.

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Data Bases

Separate sets of data were used in the two portions of the study. The first set of data was for a spacing study in which stem measurements were made on standing sample trees. The measurements were (1) total tree height, in feet; (2) Hohenadl's (Heger 1965) five diameters at fixed proportions of total tree height, plus (3) four additional diameters as proposed by Altherr (1960). The points of bole diameter measurement, expressed as fractions of the distance from the tree tip down, were: D.1, D.3, D.5, D.7, D.82, D.86, D.9, D.94, and D.98 as well as DBH (4.5 feet above ground). Diameters were measured both outside and inside bark.

The second set of data was for trees collected for volume table construction. Data for 638 sample trees were collected by the Pacific Northwest Forest and Range Experiment Station, USDA Forest Service; the Weyerhaeuser Company; and the State of Washington, Department of Natural Resources. The data were pooled to improve the standard volume equation for western hemlock, and results have been reported (Chambers and Foltz 1979, Wiley and others 1978). The trees had been measured for diameter outside and inside bark beginning at the stump and at 8- to 20-foot intervals thereafter to the tree tip. Tree DBH and total height were also measured.

Study of Form Quotient Change

Methods

Sample tree description.—Initial spacing treatments might cause form quotient and volume differences that would be undetected by tree height and diameter measurements alone. By using special instruments and climbing standing trees, nine bole measurements were made periodically for 4 years of an 8-year period on each of nine trees on two plots in three spacings. Height and DBH were measured annually for the 8 years. The three spacings were 4, 9, and 22 feet. All plots had been spaced to about 4 feet 2 years prior to treatment. Trees averaged 20 feet tall at first treatment and grew to about 45 feet after 8 years.

The use of mean tarif number for volume calculations.—The sample trees are the basis for assigning volume to all trees in a plot at each remeasurement. The procedure for assigning plot volume is the tarif system (Turnbull and others 1963), which uses the recognized linear relationship of tree volume to basal area in even-aged stands (Hummel 1955). From the assortment of volume lines provided by the tarif system, the appropriate volume-basal-area line is selected for each sample tree at each remeasurement. (Established mathematical relationships describe the selection process. Either direct tree measurements or height-diameter-volume equations may be used to estimate tree volume for use in the process.) Each line so selected has a unique, representative tarif number. The average tarif number for all the sample trees on a plot identifies the average volume-basal-area line for each plot.

Mean tarif number at each plot remeasurement is a direct index to the volume line. In this study the tarif procedure was used to compare two sources of the volume line; one was assigned from a standard volume equation and the other was calculated from stem measurements. Expressing the volume lines in terms of mean tarif number allows direct comparison of the sources of volume estimates. Significant differences of mean tarif number between the two sources imply that there is a difference in the underlying relationship of volume to basal area for the sources.

Table 2—The most useful tree volume equations with coefficients

Equation number	Equation coefficient	Variable
5	log CVTS = −2.73456265	
	+ 1.03313233	log ($DBH^2 \times H$)
	+ .10407758	$(D.9/DBH)^2$
	+ 1.32901244	log (D.7/DBH)
	− .00221155	DBH
7	log CVTS = −3.37857130	
	+ 1.00767318	log ($D.9^2 \times H$)
	+ .89111553	$(D.5/D.9)^{0.5}$
8	log CVTS = −3.40978986	
	+ 1.00915622	log ($D.9^2 \times H$)
	+ .59387586	$(D.5/D.9)^{0.5}$
	+ .31320765	(D.7/D.9)
10	log CVTS = −2.71907159	
	+ 2.02477817	log DBH
	− .00590929	DBH
	+ 1.07716464	log H
12	log CVTS = −2.53283870	
	+ 2.03621703	log DBH
	− .00140209	DBH
	+ 1.01277022	log H
	+ 1.76284601	log (D.9/DBH)
	+ .36689238	$\log (D.5/D.9)^2$

CVTS = total tree cubic foot volume inside bark;

log = logarithm to base 10;

H = total tree height above ground, in feet;

DBH = diameter outside bark at 4.5 feet above ground; and

D.5, D.7, D.9 = diameter outside bark at 0.5, 0.7, and 0.9 of total tree height from the tip down.

Change of tarif number with treatment and time.—Estimates of mean tarif number from stem measurements and the standard volume equation were nearly the same in 1972. Average differences were 0.5, 0.1, and 1.1 tarif units for the three treatments and were statistically nonsignificant. Mean tarif numbers became statistically significant (at the 5-percent confidence level) with time and developed different trends (fig. 1). The two techniques produced significantly different volume relationships for treatments.

Influence of volume estimation method on volume.—The standard volume equation overestimated volume derived from upper stem measurements by an amount that was in direct proportion to the difference in tarif number. By 1978 the standard volume equation overestimated the 9-foot spacing by 7 percent and the 22-foot spacing by 12 percent.

Conclusions

The standard volume equation, by its insensitivity to differences in tree form, significantly overestimated volume in these young stands.

It is uncertain what the future course of treatment differences will be; therefore, future measurements should allow evaluation of tree form. Dendrometer measurements along the full bole of well-crowned western hemlock trees will be difficult. A method is needed that includes form quotients in the volume estimating process. The next section describes development of such a method.

Measured Form as a Third Variable in Diameter-Height Volume Equations

Background

Volume equations, which depend just on height and diameter, account for tree form differences only to the extent that form is predictable from height and diameter. Volume depends on a combination of diameter, height, and form, yet only rarely is form included as an additional variable in standard volume equations. In the Pacific Northwest, tree volume tables often use a fixed point on the upper bole, usually 16 or 32 feet above ground, as a basis for a form measurement.

Heger (1965) in his application of Hohenadl's method reemphasizes that tree shape can be characterized using form quotients for diameters selected at proportional points of reference on the tree bole. As shown in the appendix, (D.5/D.9) is a form quotient that represents shape of the tree and is highly correlated with tree volume. Reukema (1971) uses D.5 as a basis for form-volume estimation and Roebbelen and Smith (1981) find that a diameter measurement at half height improves the precision of volume estimation. To some extent, the lower bole form quotient, (D.9/DBH), represents the influence of measuring diameters at proportional heights among short and tall trees.

Pollanschultz (1966) examines form functions and volume equations derived from them. He uses the variables DBH, total height, and stem diameters at "0.1, 0.3, and 0.5 of total height"—the equivalent of D.9, D.7, and D.5, respectively, as defined here. He finds that combinations of these primary variables effectively reduce standard deviation of form-function equations. Schmid-Haas and Winzeler (1981) find that including upper stem diameter is very important for tree volume estimation. They use either diameter D.7, as defined here, or the diameter at a fixed height of 23 feet. They find that volume functions using only diameter at breast height provided volume estimates with standard deviations 30 to 110 percent higher than volume functions with form included when the same instruments were used for both. It is clear that including a form variable increases the precision of tree volume equations.

Based on these findings, it was expected that (D.5/D.9), (D.7/DBH), (D.7/D.9), (D.9/DBH), or their transformations would provide direct estimates of tree form that would serve as variables together with diameter and height in a tree volume equation. These quotients are easily measured on standing trees with a Spiegel relaskop, provided the points are visible, and require less time to estimate than does complete stem dendrometry.

Methods

The most recent effort (Chambers and Foltz 1979) to strengthen the standard volume tables for western hemlock combined existing tree data with additional data for felled large trees. In all, 638 trees with detailed stem measurements were available for analysis.

Computing tree volume and interpolating for missing diameters.—Cubic foot volume of each section was computed as that of a frustum of a neiloid or of a paraboloid for sections of the bole between the stump and the tip section. A plotted sample of 19 representative trees showed that the paraboloid was appropriate for tree sections occurring at distances up to 93 percent of the distance from the tree tip to the ground. The neiloid was appropriate for tree sections occurring in the remaining 7 percent of the distance. Exceptions to this were trees less than 45 feet tall, which were treated as neiloids from stump to DBH. The inflection point at 93 percent of the distance from the tip is lower than the 75 to 80 percent for all species that Demaerschalk and Kozak (1977) note.

Volume of the tip section was computed as that of a cone, and volume of the stump as that of a cylinder using stump diameter. The volume computed from each section was summed to total wood volume, inside bark.

Only a small part of the data base had direct measurements for D.5, D.7, and D.9. These missing measurements were estimated by interpolating for diameters using both paraboloidal and neiloidal equations for appropriate cross section areas of each tree. Diameters that resulted from using these formulas were the same as those produced using a direct linear interpolation of section diameters because the tree sections were relatively short.

Grosenbaugh (1966) states that it matters little which formula is used for interpolation provided the distance between measured points is short. He recommends distances such that the one measured diameter is within 20 percent of the diameter of the other. A random sample of 25 trees in this study showed that only 7 percent of the three lower bole interpolations exceeded Grosenbaugh's recommendation; 5 of that 7 percent were measurements on short trees where the interpolation was between measurements only 4 feet apart.

The following form quotients were computed using outside bark measurements: (D.5/D.9), (D.7/D.9), (D.9/DBH), and (D.7/DBH). In addition, the logarithm, the square, and the square root of each form quotient were computed and each multiplied by tree height and included as variables in regression analysis. The variables and transformations selected by step-wise multiple regression appear in table 1.

Testing results using the measured range of form quotient values.—Original tree data were arrayed in order by values of height and diameter, listing log (D.9/DBH), log (D.7/DBH), and log $(D.5/D.9)^2$.From this array, maximum and minimum values of the three form quotients were plotted over height for similar sample trees having diameters within 0.8 inch and heights within 0.5 foot of each other.

The data had distinct trends, but because there were never more than two to four trees with similar diameter and height, the plotted points of maximum and minimum values for the form quotients were erratic. Trends of the average high and average low values for the appropriate form quotients were smoothed by hand and used to estimate volume in equation 12. (Equation 12 is directly comparable to equation 10, the form most commonly used in the Pacific Northwest.) These volumes are practical estimates of the influence of the form quotients on volume accuracy when diameter and height are held constant. The smoothed values are summarized in table 3.

Table 3—Smoothed high and low values of 3 form quotients; sample tree diameter at breast height and total tree height are held constant

		Form quotients					
DBH	Height	D.9/DBH		D.7/DBH		D.5/D.9	
Inches	*Feet*						
2.2	20	1.05	1.29	0.87	0.94	0.39	0.60
4.6	30	1.02	1.11	.83	.88	.52	.69
5.0	50	.99	1.00	.83	.88	.71	.79
10.0	70	.97	.99	.83	.88	.72	.77
10.3	100	.94	.97	.82	.88	.71	.76
15.0	110	.94	.97	.82	.88	.71	.76
17.0	120	.93	.96	.81	.88	.70	.75
18.0	130	.93	.96	.80	.87	.69	.74
18.0	140	.92	.96	.77	.86	.69	.73
33.0	160	.91	.96	.73	.85	.67	.71
25.0	180	.90	.96	.70	.83	.62	.65

The trees used earlier in the study were also examined to determine the range of form quotients as they occur in comparable stands subjected to early spacing treatment. The results are in table 4.

Table 4—Range of values of individual tree form quotients, paired stands,[1] thinned to different early spacings

Stand and treatment	Number of trees	DBH	Height	Form quotients		
				D.9/DBH	D.7/DBH	D.5/D.9
		Inches	*Feet*			
1979:						
4-foot spacing	10	3.6-5.8	35-46	1.00-1.08	0.85-0.98	0.70-0.83
22-foot spacing	10	6.9-10.1	36-45	1.00-1.03	.75-.84	.49-.59
1975:						
4-foot spacing	14	2.9-4.8	28-39	1.00-1.03	.79-.97	.51-.73
22-foot spacing	11	4.4-6.0	25-36	1.00-1.11	.60-.94	.45-.53

[1]Data from two ages of stands described in the first part of the study.

Twenty-three pairs of trees representing the total range of diameters and heights in the data base had nearly identical height and diameter. Volume differences of the paired trees ranged from 4 to 30 percent and averaged 11 percent. They were examined to see if the form of the lower bole (D.9/DBH) had greater influence on volume than did upper tree form (D.5 D.9). Of the 23 cases, (D.9/DBH) alone had greater influence on volume in 8 cases; (D.5/D.9) predominated in 3 cases and the two ratios shared influence in 10 cases. In 2 cases it was unclear which had more influence.

Useful equations were desired to supplement the main purposes of the study. The tarif volume-estimating procedure (Turnbull and others 1963) allows direct estimation of tree volume in a stand by averaging sample-tree tarif numbers. This avoids the need for fitting tree height-diameter curves. Estimates of tree height are often desired, however, for each tree on a plot. The data in this study allow derivation of equations for estimating tree height when volume and average tarif number are known.

Trees in the data base were assigned a tarif number based on actual tree volume according to the equations given by Brackett (1977). The data were then arrayed in ascending order of tarif number, and sequential groups of 20 trees were selected beginning with the tree of lowest tarif number. The two groups with the highest mean tarif number and the two with the lowest all had ranges of four to seven tarif number units within their respective group. The remaining groups had a range of about two tarif units. These ranges are not unusual for natural even-aged stands. Mean tarif was computed for each group of 20 trees and tree volume was estimated from mean tarif number. This estimated volume was used in equations for estimating tree height.

Results and Discussion

Tree volume equations.—The 12 equations for predicting total cubic foot volume, and appropriate statistics, are in table 1. Selected equations complete with coefficients are in table 2. All variables included in each equation were significant at the 5 percent level of probability or higher.

Form quotients contributed significantly to increased precision of the cubic-foot volume estimate. Equations 2, 3, 4, and 5 added form quotients to the variable log ($DBH^2 \times H$) used alone in equation 1. In a similar way, equations 7 and 8 added form quotients to log ($D.9^2 \times H$) used in equation 6. Equations 11 and 12 added to log (DBH) and log (H) used in equation 10. The contribution of each variable is visible in terms of increased value of R^2 and in decreased value of the standard error of estimate in both logarithmic and antilog form, as shown in table 1.

Several form quotients including the variable D.5 were required to minimize the standard error of estimate (equation 4). Equations 5, 9, and 11 in table 1 exclude the variable D.5 and can be used on standing trees with relatively long crowns where D.5 is not visible. Equations 5 and 9 have lower standard errors of estimate than does equation 11. Equation 5 uses all the form variables as quotients, which makes it more convenient for field use than the variables in equation 9. For these reasons, equation 5 was considered as the most useful and was examined more thoroughly.

The residuals of equation 5 (in logarithmic form), when plotted with respect to its variables, had neither trends nor imbalanced variance. The residuals also had no bias when converted from the logarithmic form to actual values of each variable. Variance was not homogeneous, however. When trees were less than 45 feet tall, and D.9 was at or below the tree DBH, and the quotient (D.9/DBH) was 1.00 or larger, there was less variance than when the quotient was less than 1.00. Also, most of the volume variance with respect to form quotient (D.5/D.9) occurred between quotient values of 0.6 to 0.8. For values above and below this range, there was less variance. Using the logarithmic form of the variables balanced the variance and maintained the requirements of regression analysis.

The value of the form variable related slightly to values of other independent variables; however, not to an extent that multicollinearity was considered to be a problem. Even with some multicollinearity, the equation parameters would provide unbiased estimates of volume.

The single form variable in equation 2 was stable with respect to tree diameter and height. Logarithm of volume was plotted over log ($DBH^2 \times H$) for four equal divisions of the total range of value of the form variable log (D.7/DBH). Generally, for each given level of log ($DBH^2 \times H$), log (D.7/DBH) related clearly and consistently with volume. This illustrated the reliable behavior of the form variable within the range of the highly correlated relationship of tree volume to diameter and height.

Equation 10 was the equivalent of the equation given by Chambers and Foltz (1979); however, the coefficients were not identical. The coefficients differed because for this study the shape of the tree bole was treated as a neiloid up to one-tenth of tree height from the ground; Chambers and Foltz use the neiloid only as far as DBH. The difference between the two equations is trivial.

The range of form quotient values and their effect on volume accuracy.—Volume computed from tests of equation 12 shows that the influence of form has practical significance. The equation was solved using smoothed values for the average high and average low of the two form quotients while holding height and diameter constant.

Tree volume computed from the average high form quotients differed by about 9 percent from volume computed from the average lows for trees over 45 feet tall. Differences in volume in percent were 24, 40, 30, and 20 for trees 25, 30, 35, and 40 feet tall, respectively. Half the sample trees in the study had form quotient values outside the average highs and lows used in this test. If extreme values of form quotient are used, two trees over 45 feet tall with the same diameter and height could differ in cubic volume by as much as 18 percent. This difference, definable by using form quotients, would be unidentified when only tree diameter and height are known.

The smoothed high and low values of three form quotients (table 3) conservatively estimate form quotient variation when tree diameter and height are held constant. There was limited data to test the range of form quotient values on the treated stands described in the first part of this study. These ranges (table 4) are greater than those listed in table 3. The form values define differences among trees in widely and closely spaced stands. The values in table 4 in their respective equations translate into volume differences similar to those discussed in the first part of this study. In short, tree volume estimated by the equation was similar to volume that had been calculated originally from carefully measured tree stem diameters on trees not included among those used to generate the volume equations.

The examination of effects of (D.9/DBH) and (D.5/D.9) on the volume of matched trees with identical DBH and height confirms a fact that can be deduced by considering the significant variables of the equations in table 1: That is, differences in form on the portion of a tree between DBH and D.9 and differences in form between D.9 and D.5 are both important in accounting for volume difference of trees with the same DBH and height.

Useful supplemental equations—Two equations given below estimate tree height when tree volume and average tarif are known. All variables in each equation had significant F-values at the 95-percent confidence level or higher. Plotted residuals for each variable showed neither bias nor imbalanced variance. Lowest standard error of estimate per given number of values was obtained when form quotients were included in the regression. An equation was derived for use when form quotients are unknown.

$$\log H = 1.10955627 + 0.25628328 \log (\text{volume}) + 0.57283175 \log (\text{mean tarif}) - 0.78736802 \log (D.9/DBH) - 0.29643368 (D.7/DBH)^2 - 0.07043974 (DBH)^{.5};$$

where: $R^2 = 0.994$ and standard error of estimate, log form $= 0.0208$.

$$\log H = 0.70413539 + 0.24535889 \log (\text{volume}) - 0.01412038 (\text{volume})^{.5} + 0.59564993 \log (\text{mean tarif}) + 0.00010283 DBH^2$$

where: $R^2 = 0.982$ and standard error of estimate $= 0.0372$.

Mean tarif is the average of 20 trees. Volume in cubic feet for the total tree bole is estimated from mean tarif. Log is logarithm to base 10 and form quotients are as defined previously.

Conclusions

As expected, using one or more form quotients increased the precision of volume computation beyond that given by standard volume equations that exclude a form variable. With height and diameter held constant, differences in stem form can lead to tree volume differences between 9 and 18 percent in trees over 45 feet tall. This is important, especially in cases where stand treatment can cause extreme differences in tree form.

Equation 8 is one of the two most precise of those given in table 2, but it requires estimates of D.9, D.7, and D.5 as well as height. Equation 5 is less precise than equation 8 but eliminates stem measurement at D.5, a point that is frequently not visible on standing trees. All form quotients are easily measured on standing trees with a Spiegel relaskop if the measurement points are visible from the ground.

Both equations 5 and 8 allow direct use of a form quotient when estimating tree volume. The added field measurement effort required is relatively small compared with taking multiple relaskop bole measurements up the whole tree stem length or felling trees for stem measurements. The equations adequately estimate the influence of stem form in treated western hemlock stands at a reasonable cost in time and effort. One needs to understand the influence of upper stem form to properly interpret results of spacing treatments. Such information is frequently lacking.

The procedure used here has other potential applications. Numerous collections of data on tree volume exist for various species but few, if any, have direct measurements of diameter at desired proportions of height. Because the interpolated estimates of these diameters proved to be effective in this study, similar success is likely if the method were applied to other tree species.

Acknowledgments

Thanks are extended to Bruce W. Foltz and Jon Swanzy, State of Washington, Department of Natural Resources, for their help with the processing of the data. Thanks are also extended to the Weyerhaeuser Company for sharing data on felled trees, and to the Pacific Northwest Forest and Range Experiment Station, USDA Forest Service, who provided original data on felled trees from past work and funded collection of data for additional large-diameter trees.

Metric Equivalents

The nominal height of 4.5 feet for measuring tree diameter is equivalent to 1.37 meters.

1 foot = 0.3048 meter
1 inch = 2.54 centimeters
1 cubic foot = 0.0283168 cubic meter

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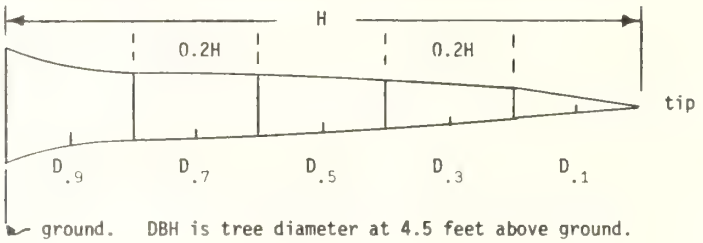
Appendix

A. GIVEN: TREE DIMENSIONS WITH STEM MEASUREMENT AT 5 PROPORTIONAL POINTS:



B. IT FOLLOWS THAT:

1. LOG VOLUME FOR EACH OF THE FIVE SECTIONS USING SECTION MID-POINTS AND WITH DIAMETER AND LENGTH IN THE SAME UNITS OF MEASURE IS:

$$CV = \frac{\pi}{4}(0.2H)D_x^2$$

2. TOTAL TREE VOLUME, CVTS, IS THE SUM OF THE VOLUME OF THE FIVE SECTIONS:

$$CVTS = \frac{\pi}{4}(0.2H)\left[D_{.9}^2 + D_{.7}^2 + D_{.5}^2 + D_{.3}^2 + D_{.1}^2 \right]$$

$$= \frac{\pi}{4}(D_{.9}^2)\,0.2H\left[1.00 + \left(\frac{D_{.7}}{D_{.9}}\right)^2 + \left(\frac{D_{.5}}{D_{.9}}\right)^2 + \left(\frac{D_{.3}}{D_{.9}}\right)^2 + \left(\frac{D_{.1}}{D_{.9}}\right)^2 \right]$$

3. THE RATIO OF TREE VOLUME TO VOLUME OF A CYLINDER OF DIAMETER $D_{.9}$ AND LENGTH H IS CALLED $LAMBDA_{.9}$ AND IS A REDUCTION FACTOR THAT ADJUSTS CYLINDER VOLUME TO VOLUME OF THE TREE SHAPE AND HENCE IS A "NATURAL" OR "TRUE" FACTOR.

$$LAMBDA_{.9} = \frac{CVTS}{\frac{\pi}{4}(D_{.9})^2 H} = 0.2\left[1.00 + \left(\frac{D_{.7}}{D_{.9}}\right)^2 + \left(\frac{D_{.5}}{D_{.9}}\right)^2 + \left(\frac{D_{.3}}{D_{.9}}\right)^2 + \left(\frac{D_{.1}}{D_{.9}}\right)^2 \right]$$

4. $LAMBDA_{.9}$ IS HIGHLY CORRELATED WITH $\left(\frac{D_{.5}}{D_{.9}}\right)^2$

$$LAMBDA_{.9} = b\left(\frac{D_{.5}}{D_{.9}}\right)^2 + a$$

5. Fbh = $CVTS/(DBH)^2(H)$ = BREAST HEIGHT FORM FACTOR.

$$Fbh = LAMBDA_{.9}/(DBH/D_{.9})^2 = (D_{.9}/DBH)^2\,(LAMBDA_{.9})$$ -- PRODAN, 1965, PAGE 50

C. THEREFORE:

1. $(D_{.5}/D_{.9})^2$ REPRESENTS SHAPE OF STEM, THAT IS, THE "TRUE" FORM FACTOR.

2. $(D_{.9}/DBH)^2$ REPRESENTS, AT LEAST IN PART, THE EFFECT OF DIFFERING PROPORTIONAL HEIGHTS OF MEASUREMENTS ON TREES OF DIFFERENT HEIGHT.

3. Fbh THE BREAST HEIGHT FORM FACTOR, IS A COMBINATION OF (1) AND (2).

THE SQUARE ROOT OF (1) IS IDENTIFIED AS A "TRUE" FORM FACTOR (HEGER, 1965) AND THE SQUARE ROOT OF (2), INVERTED, AS HOHENADL'S FORM QUOTIENT. (ASSMANN, 1970).

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The study reviews Hohenadl's procedure for defining form quotients and tree volume from diameters measured at fixed proportions of total tree height. Modifications of Hohenadl's procedure were applied to two sets of data for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) from the Pacific Northwest. The procedure was used to define volume differences in thinned stands, and selected form quotients were used as variables to improve accuracy and precision of standard tree volume equations. Estimating form quotients on standing trees requires less time than complete stem dendrometry. The technique has application to other tree species.

Keywords: Volume estimation, volume equations, form factors, form quotient, western hemlock.

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